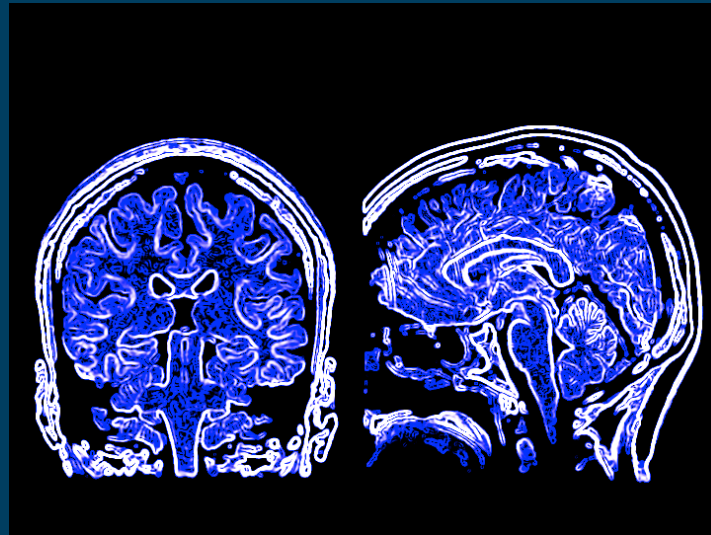# frontiers
RESEARCH TOPICS

EDUCATIONAL NEUROSCIENCE, CONSTRUCTIVIST LEARNING, AND THE MEDIATION OF LEARNING AND CREATIVITY IN THE 21ST CENTURY

Topic Editor
Layne Kalbfleisch

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EDUCATIONAL NEUROSCIENCE, CONSTRUCTIVIST LEARNING, AND THE MEDIATION OF LEARNING AND CREATIVITY IN THE 21ST CENTURY

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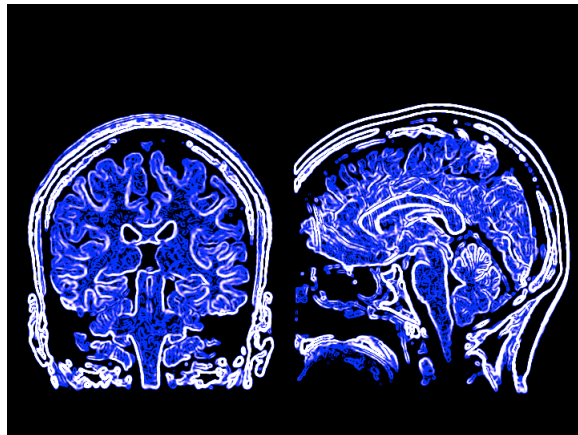
Image by Dr Layne Kalbfleisch.

The advent of educational neuroscience, a transdisciplinary exercise emerging from cognitive neuroscience and educational psychology, is the examination of physiological processes that undermine, support, and enhance the capacities to learn and create. The physiological underpinnings of learning and creativity each impact human ability and performance and mediate the processes of becoming educated, expert, and valued. Evidence of learning provides support to an ongoing canon, process, system, field or domain, while evidence of creativity results in an elaboration or departure from an ongoing canon, process, system, field, or domain. Educational neuroscience extends a challenge to scholars from multiple contexts to engage in the characterization and exploration of human ability and performance in these realms. The role of context, both environmental and interoceptive, is an integral part of efforts in educational neuroscience and in theories of constructivist learning to contribute ecologically valid insight to the pragmatic processes of learning and creativity. Examination at this level of specificity is vital to our ability to educate and support human potential in the 21st century. This Research Topic examines the neural basis of cognitive states and processes that influence knowledge and skill acquisition tied to the demonstration of human ability and performance across individual differences and in multiple contexts including STEM learning and the arts.

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Educational neuroscience, constructivism, and the mediation of learning and creativity in the 21st century

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Elephant. Imagine one standing right in front of you. Why begin this editorial on educational neuroscience and constructivist learning with an elephant? Because in many ways, this book illustrates the old parable of the blind man who has his hand on the elephant. More specifically, he has his hand on *part* of the elephant (his flank? his trunk?). And that part, in and of itself, informs the blind man's understanding of the elephant as the thing in itself. Yet, a compadre standing with him also has *his* hand on the elephant and commands his own subjective conception of and experience with the great mammal.

The call for this special topic was intentionally broad and conceptually ambitious, to coalesce state-of-the art research across multiple domains that would collectively give shape to the emerging field of educational neuroscience. This book spans a body of work that represents the efforts of 60 contributors and took 14 months to publish from the first article (on neuromyth) to the last (on the multiple intelligences). That shape, provided by nine original research papers, two reviews, and one perspective article, pragmatically demonstrates one of the most difficult existing theoretical proofs in the field of educational psychology—constructivist learning. Both ubiquitous in its influence (the grand challenge?) and hard to parse (the elephant in the room?), each paper in this book gives rise to a piece of the elephant *constructivism*. An idea blueprinted by Vygotsky, Dewey, and Bruner, and now instantiated in this series of papers, tackles the issues of learning, transfer, and experience with multiple metrics (from survey research to various neuroimaging techniques) across domain general (creativity, reasoning) and specific ("three R" learning, music) processes and accounts for the influences of state (motivation), genetics (in reading disability), and arousal (sleepiness). Three aspects of constructivism arise from this collective: the influence of context on human learning and performance, training influences on neural plasticity and learning transfer, and the assessment of individual differences. This modern interpretation illustrates the potential of educational neuroscience to answer "how," "why," and "when" individual differences matter and when we've struck upon a piece of universal knowledge.

Intervention science is still in its infancy and overlaps our efforts to norm the basic developmental trajectories of the brain across life. In my opinion, learning context is the great divide between educators and neuroscientists simply because the scales of measurement are so different. In response, these papers are examples of the intellectual risk, curiosity, and transdisciplinary thought that narrow that divide. For example, musicologist Alexander Khalil poses the idea that training young children to synchronize their playing of the Balinese gamelan may, perhaps, influence more general tendencies to self-regulate and attend. In that same vein, Nina Kraus' team reveals that music training in adolescence may help the brain better contend with distraction. Todd Lubart and his team add "matter" into the ongoing discussion about the contingencies of creativity, what it is and means in different contexts, and how we might assess it usefully. Jelle Jolles, Paul Howard Jones and colleagues attempt an "epidemiology" of neuromyth in order to assess the influence of this roadblock in our understanding of the learning process. Other articles span a range that includes: articulating rules and methods for understanding the relationship between genetics and behavior in reading disability, assessing how sleep quality may impact performance in school, the context in which transfer may occur between linguistic training, reading, and writing skills in college students, and arithmetic fact learning and retrieval in numerical and nonverbal problem solving contexts.

In an age where complexity is beginning to define how we understand our cities, other pandemic dynamical systems, and even ourselves, we cannot, for the sake of education, afford to dismiss this theory's complexity. Because it is articulated from multiple historical and contemporary perspectives suggests an explanatory power that, while complex, will eventually simplify and collapse our understanding of the learning process to the best set of first principles that can re-populate and position our understanding of what education ought to be and look like no matter the context. After all, that is the goal of educational neuroscience—to apply the tools, metrics, and methods of neuroscience to questions and problems of human learning in order to inform aspects of curriculum design, pedagogy, and human performance in both formal and informal learning contexts.

Though this research topic is conceptually broad and perhaps "wider than the sky" would say Emily Dickinson, it is a necessary first cut to re-define the blueprint of constructivist learning according to the tools, metrics, and methods that modern neuroscience provides us. And with that, the need to educate readers so that they become literate consumers of this new technical genre so that we can arrest the impact of existing neuromythologies

and curtail the proliferation of new ones. And so the elephant emerges again as a metaphor. Elephants possess a fantastic memory. They remind us how fundamental the learning process is to survival and a capacity to thrive individually and socially. They remind us that though the proposition of understanding learning is impossibly large, that we can take a crack at it, see what happens when we do, and, in the end, through new knowledge and reflection, learn from our own experience.

Conflict of Interest Statement: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Neuromyths in education: Prevalence and predictors of misconceptions among teachers

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The OECD's Brain and Learning project (2002) emphasized that many misconceptions about the brain exist among professionals in the field of education. Though these so-called "neuromyths" are loosely based on scientific facts, they may have adverse effects on educational practice. The present study investigated the prevalence and predictors of neuromyths among teachers in selected regions in the United Kingdom and the Netherlands. A large observational survey design was used to assess general knowledge of the brain and neuromyths. The sample comprised 242 primary and secondary school teachers who were interested in the neuroscience of learning. It would be of concern if neuromyths were found in this sample, as these teachers may want to use these incorrect interpretations of neuroscience findings in their teaching practice. Participants completed an online survey containing 32 statements about the brain and its influence on learning, of which 15 were neuromyths. Additional data was collected regarding background variables (e.g., age, sex, school type). Results showed that on average, teachers believed 49% of the neuromyths, particularly myths related to commercialized educational programs. Around 70% of the general knowledge statements were answered correctly. Teachers who read popular science magazines achieved higher scores on general knowledge questions. More general knowledge also predicted an increased belief in neuromyths. These findings suggest that teachers who are enthusiastic about the possible application of neuroscience findings in the classroom find it difficult to distinguish pseudoscience from scientific facts. Possessing greater general knowledge about the brain does not appear to protect teachers from believing in neuromyths. This demonstrates the need for enhanced interdisciplinary communication to reduce such misunderstandings in the future and establish a successful collaboration between neuroscience and education.

Keywords: neuromyths, educational neuroscience, prevalence, predictors, teachers

INTRODUCTION

There is widespread interest among teachers in the application of neuroscientific research findings in educational practice. Neuroscientific research has received a lot of attention since 1990–2000, which was declared the "Decade of the Brain" in the United States. Yet, the field of neuroscience is complex and the accurate transfer of research findings to the classroom is often difficult (Jolles et al., 2005; Devonshire and Dommett, 2010; Ansari et al., 2011). This gap between neuroscience and education has enabled many misconceptions about scientific findings to occur (Goswami, 2006). In 2002, the Brain and Learning project of the Organization for Economic Co-operation and Development (OECD) drew international attention to this phenomenon. The organization raised concerns with regards to the rapid proliferation of so-called "neuromyths". These were defined as "a misconception generated by a misunderstanding, a misreading, or a misquoting of facts scientifically established (by brain research) to make a case for use of brain research in education and other contexts" (Organisation for Economic Co-operation, and Development, 2002). The influence of these myths in the classroom is problematic because it wastes money, time, and effort, which could be better spent on the development of evidence-based practices (Sylvan and Christodoulou, 2010; Pasquinelli, 2012). Despite concerns regarding the rapid proliferation of neuromyths (e.g., Goswami, 2006), not much is known about the prevalence of neuromyths among professionals in the field of education. The current study investigated if belief in neuromyths was common among teachers that were interested in the neuroscience of learning. It would be of concern if neuromyths were found in this sample, because these teachers will be most eager to implement (wrong) brain-based ideas in educational practice. Furthermore, these teachers might promote the circulation of myths and spread their ideas to teachers who are less engaged and acknowledged with brain research. In addition to examining the prevalence of neuromyths, the study also investigated which myths were most and least prevalent. To shed light on how the proliferation of myths may differ between countries, teachers from specific regions in both the United Kingdom (UK) and the Netherlands (NL) were involved. Additionally, this study focused on identifying factors that predict belief in neuromyths.

Although neuromyths are incorrect assertions about how the brain is involved in learning, their origin often lies in genuine scientific findings. An example of a neuromyth is that learning could be improved if children were classified and taught according to their preferred learning style. This misconception is based on a valid research finding, namely that visual, auditory, and kinesthetic information is processed in different parts of the brain. However, these separate structures in the brain are highly interconnected and there is profound cross-modal activation and transfer of information between sensory modalities (Gilmore et al., 2007). Thus, it is incorrect to assume that only one sensory modality is involved with information processing. Furthermore, although individuals may have preferences for the modality through which they receive information [either visual, auditory, or kinesthetic (VAK)], research has shown that children do not process information more effectively when they are educated according to their preferred learning style (Coffield et al., 2004). Other examples of neuromyths include such ideas as "we only use 10% of our brain", "there are multiple intelligences", "there are left- and right brain learners", "there are critical periods for learning" and "certain types of food can influence brain functioning" (e.g., Organisation for Economic Co-operation, and Development, 2002; Geake, 2008; Purdy, 2008; Howard-Jones, 2010). Some of these misunderstandings have served as a basis for popular educational programs, like Brain Gym or the VAK approach (classifying students according to a VAK learning style). These programs claim to be "brain-based" but lack scientific validation (Krätzig and Arbuthnott, 2006; Waterhouse, 2006; Stephenson, 2009; Lindell and Kidd, 2011). A fast commercialization has led to a spread of these programs into classrooms around the world.

Yet, only a few studies have examined the prevalence of misunderstandings about the mind and brain. A study examining neuroscience knowledge in the general population of Brazil revealed that many misconceptions existed among the general public, and that there was a lot of variation in the frequency of these misunderstandings (Herculano-Houzel, 2002). The statement "we only use 10% of our brain", defined by the Organisation for Economic Co-operation, and Development (2002) as a neuromyth, was the most prevalent misconception among the public. Neuromyths were also found to be prevalent among trainee teachers (Howard-Jones et al., 2009). In particular, myths related to commercial brain-based educational programs were commonly accepted. Furthermore, the research showed that many trainee teachers in the UK (56–83%) had encountered one or more of these commercial brain-based programs (e.g., Brain Gym or VAK approach) in their school. To our knowledge, no studies have examined the prevalence of neuromyths among teachers who are interested in the neuroscience of learning. Furthermore, it is unclear how the implementation of brain-based programs differs across countries.

Next to examining the prevalence of neuromyths, it is important to identify the factors that predict a high susceptibility to believing in myths. Experimental research has shown that people are generally more likely to believe research findings when they are accompanied by brain images and neuroscience explanations, even when these are incorrect (Weisberg et al., 2007; McCabe and Castel, 2008). Weisberg et al. (2007) found that the public's perception of a poor explanation became more positive when neuroscience

was included, even though the neuroscience was irrelevant. This may lead to misjudgments of scientific evidence. Furthermore, it may be difficult for people who lack neuroscientific expertise to recognize misconceptions about brain research in the popular media. Information provided by the popular media is often over-simplified or over-interpreted, as the popular media aims to reach many people. Therefore, popular media have been held responsible for creating misconceptions (Wallace, 1993; Beck, 2010). Apparent simplicity in popular articles may lead to the flawed assumption that complex neuroscience is easily applicable in the classroom. When people lack a general understanding of the brain and do not critically reflect on their readings, they may be more vulnerable to neuromyths. Thus, a lack of neuroscience literacy and reading popular media may be factors that predict the number of misconceptions teachers have about the brain.

Consequently, neuroscience literacy (i.e., a general understanding of the brain) may protect against incorrect ideas linking neuroscience and education. Support for this hypothesis was found in a sample of trainee teachers (Howard-Jones et al., 2009), where general knowledge of the brain related positively to the ability to identify neuromyths. This suggests that neuroscience literacy is an important factor that enables individuals to differentiate science from pseudoscience. Fortunately, many teachers are eager to increase their neuroscience literacy (Pickering and Howard-Jones, 2007; Hook and Farah, 2012). Attempts to increase their literacy most often included in-service training about the brain (Pickering and Howard-Jones, 2007), which has been identified as a strong predictor of neuroscience literacy (Herculano-Houzel, 2002). Next to in-service training, neuroscience literacy has been predicted by reading popular science magazines and newspapers (Herculano-Houzel, 2002). Thus, reading popular media seems to have both beneficial effects (higher neuroscience literacy) and negative effects (creating misconceptions).

The present study investigated the neuroscience literacy and prevalence of neuromyths among primary and secondary school teachers in the UK and the NL. The sample consisted of teachers who indicated they were interested in the neuroscience of learning. It would be of concern if neuromyths were found in this sample, as these teachers may want to use these incorrect interpretations of neuroscience findings in their teaching practice. By including teachers from both the UK and the NL, it was possible to examine possible differences between countries and the educational systems therein. The study aimed to give an indication of the prevalence and predictors of myths among teachers in primary and secondary school. It is therefore of potential importance for the development of educational innovations which target teachers' knowledge of neuroscience. The second aim of the study was to examine a range of factors that might be associated with belief in neuromyths such as reading popular science magazines. Teachers completed a survey comprising neuromyths and general assertions about the brain and its involvement in learning. The hypotheses were that myths related to commercialized educational programs would be the most prevalent of the myths presented. General knowledge and in-service training were expected to have a protective effect on the belief in myths. Furthermore, it was hypothesized that teachers who read popular science magazines would believe more neuromyths. Therefore, we additionally investigated whether certain

teacher characteristics (e.g., age, sex, primary/secondary school teacher) were associated with knowledge and the number of myths. By this means, the study will provide valuable information about the possible prevention of neuromyths in education.

MATERIALS AND METHODS
PARTICIPANTS
The total sample of 242 participants included 137 teachers from the Dorset region of the UK and 105 teachers from several regions in the NL surrounding the Amsterdam area. Participants were primary school teachers (44%), secondary school teachers (50%), and other teachers (e.g., trainee teachers, teachers in special education, teaching assistants; 6%). The schools from which the teachers were drawn could be considered a random selection of primary and secondary schools in the UK and the NL. Teachers from both countries were comparable in age [M age $= 43$ years, SD $= 11.0$; $t(180.3) = 1.16$, $p = 0.249$]. Furthermore, the distribution of primary school teachers, secondary school teachers, and other teachers was the same in both countries [$\chi^2(2, N = 241) = 2.42, p = 0.298$]. The UK sample comprised relatively more female teachers (77%) than the Dutch sample (64%), $\chi^2(1, N = 240) = 5.05, p = 0.025$. The male/female ratio did not differ between primary school, secondary school, and other teachers [$\chi^2(2, N = 240) = 5.28, p = 0.071$]. Of all teachers, 93% were interested in scientific knowledge about the brain and its influence on learning. Further, 90% of the teachers thought that this knowledge was very valuable for their teaching practice.

PROCEDURE
Schools in the selected regions were approached for participation in the research project. They were asked to forward an email with information about the research project to all teachers in their school. The research was presented as a study of how teachers think about the brain and its influence on learning. The term neuromyth was not mentioned in the information for teachers. Teachers who were interested in this topic and chose to participate, followed a link to an online survey. Average completion time was 15 min.

MEASURES
The online survey included 32 statements about the brain and its influence on learning (see Appendix). It comprised 15 statements that were educational neuromyths, as defined by the Organisation for Economic Co-operation, and Development (2002) and Howard-Jones et al. (2009), e.g., "Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual)". The other 17 statements were general assertions about the brain, e.g., "The left and right hemisphere of the brain always work together". The presentation order of myth and knowledge assertions was randomized. Answer options were "incorrect", "correct", or "do not know". Correct and incorrect assertions were balanced. Dependent variables were the percentage of incorrect answers on neuromyth assertions (where a higher percentage reflects more belief in myths) and the percentage of correct responses on general assertions.

Additionally, teachers provided background information about their age, sex, level of education [graduate or postgraduate, and whether they had a Postgraduate Certificate in Education (PGCE)]

and whether they were a teacher in primary or secondary school. They indicated whether they were interested in scientific knowledge about the brain and its influence on learning and whether they thought this knowledge was very valuable for their teaching practice. Also, they estimated the role of genes and environment in learning. Furthermore, they were asked whether they followed any in-service or other training about the brain and whether they encountered educational approaches that claimed to be brain-based in their school (Brain Gym, Learning styles, Multiple Intelligences, Left/right brain learners). Further, they indicated whether they read popular science magazines and/or scientific journals.

DATA ANALYSIS
The data was analyzed using the Statistical Package for the Social Sciences (SPSS) version 17.0 for Windows. For all analysis, a statistical threshold of $\alpha = 0.05$ was used. Independent t-tests were performed to examine differences between countries (independent variable) in percentage of neuromyths and percentage of correct responses on general statements (dependent variables). To examine which factors predicted neuromyths, a regression analysis was performed for percentage of myths (dependent variable) with country, sex, age, school type (primary/secondary school), reading popular science, reading scientific journals, in-service training, and percentage of correct answers on general assertions (predictors). A second regression analysis was performed to examine the predictors of neuroscience literacy. Percentage of correct answers on general assertions was the dependent variable, and predictors were country, sex, age, school type (primary/secondary school), reading popular science, reading scientific journals, and in-service training.

RESULTS
PREVALENCE OF NEUROMYTHS
Overall, teachers agreed with 49% of the statements promoting myths indicating that they believed these myths. There was no significant difference in overall prevalence between countries [$t(240) = 0.408, p = 0.684$]. An analysis of the responses for each myth showed a lot of variation between the myths (see **Table 1**). Seven of the 15 myth statements were believed by more than 50% of the teachers. The most prevalent of these myths were (1) "Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual, kinesthetic)", (2) "Differences in hemispheric dominance (left brain, right brain) can help explain individual differences amongst learners", and (3) "Short bouts of co-ordination exercises can improve integration of left and right hemispheric brain function". More than 80% of the teachers believed these myths. Other statements related to neuromyths were often successfully identified, e.g., "Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic)". More than 80% of the teachers answered this statement correctly.

With respect to the general statements about the brain, a difference between countries was found [$t(240) = -3.09, p = 0.002$]: Dutch teachers had higher scores on general knowledge ($M = 73\%$ correct, SD $= 12.7$) than teachers from the UK ($M = 67\%$ correct, SD $= 13.5$). Scores on knowledge did not vary with the teachers' level of education [UK: $F(4, 133) = 0.48, p = 0.748$; NL: $F(3,$

Table 1 | Correctness of responses for each myth assertion.

Neuromyth	Incorrect		Correct		Do not know	
	UK (%)	NL (%)	UK (%)	NL (%)	UK (%)	NL (%)
Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual, kinesthetic).	93	96	4	3	3	1
Differences in hemispheric dominance (left brain, right brain) can help explain individual differences amongst learners.	91	86	3	4	6	11
Short bouts of co-ordination exercises can improve integration of left and right hemispheric brain function.	88	82	0	5	12	13
Exercises that rehearse co-ordination of motor-perception skills can improve literacy skills.	78	63	3	11	19	27
Environments that are rich in stimulus improve the brains of pre-school children.	95	56	1	29	4	15
Children are less attentive after consuming sugary drinks, and/or snacks.	57	55	24	24	20	21
It has been scientifically proven that fatty acid supplements (omega-3 and omega-6) have a positive effect on academic achievement.	69	54	12	16	20	30
There are critical periods in childhood after which certain things can no longer be learned.	33	52	53	38	14	10
We only use 10% of our brain.	48	46	26	42	26	12
Regular drinking of caffeinated drinks reduces alertness.	26	36	39	41	35	23
Children must acquire their native language before a second language is learned. If they do not do so neither language will be fully acquired.	7	36	82	61	11	3
Learning problems associated with developmental differences in brain function cannot be remediated by education.	16	19	69	62	15	19
If pupils do not drink sufficient amounts of water (=6–8 glasses a day) their brains shrink.	29	16	46	49	26	35
Extended rehearsal of some mental processes can change the shape and structure of some parts of the brain.	6	14	69	58	26	28
Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic).	4	13	95	82	2	5

104) = 0.41, $p = 0.743$]. Furthermore, there were no differences between primary and secondary school teachers [$t(224) = -0.15$, $p = 0.879$].

Brain Gym (Brain Gym International, 2011), Learning Styles, and Left brain/Right brain learning programs were encountered significantly more often in schools in the UK than in the NL (see **Table 2**). More teachers from the UK than the NL followed in-service training. Dutch teachers read popular science magazines or scientific journals more often than teachers in the UK (see **Table 2**). There were significant differences between counties in teachers' views on the role of genes and environment in learning. Teachers in the NL gave considerably greater weight to genes than teachers in the UK (34 vs. 22%). Teachers in the UK attributed more to home environment (46%) and school environment (29%), compared to Dutch teachers (resp. 30 and 25%).

PREDICTORS OF NEUROMYTHS AND KNOWLEDGE
Belief in myths was significantly predicted by general knowledge of the brain ($\beta = 0.24$; see **Table 3**). This indicates that teachers with higher scores on knowledge were more likely to believe in myths. None of the other factors [country, sex, age, school type (primary/secondary school), reading popular science, reading scientific journals, or in-service training] predicted belief in myths. The model explained a significant proportion of variance ($R^2 = 0.089$) in myth scores, $F(8, 210) = 2.463$, $p = 0.014$.

General knowledge of the brain was predicted by country ($\beta = 0.16$) and reading popular science magazines ($\beta = 0.21$; see

Table 2 | Teacher characteristics.

	UK (%)	NL (%)
Encountered in school		
Brain gym	82	8
Learning styles	98	64
Multiple intelligences	71	67
Left/right brain learners	44	18
Followed in-service training	66	34
Read popular science	28	73
Read scientific journals	38	62

Table 4). This shows that knowledge was higher among Dutch teachers, and among teachers who read popular science magazines. Age, sex, school type, reading scientific journals, and following in-service training did not relate to scores on knowledge. The model explained 10% of the variance, which was significant, $F(7, 210) = 3.24$, $p = 0.003$.

DISCUSSION
This study examined general knowledge about the brain and prevalence of neuromyths among teachers in specific regions of the UK and the NL. It additionally investigated a range of candidate factors that might be associated with these outcomes. The results indicated that, overall, teachers believed half of the presented myths. Seven of the 15 myths were believed by more than

Table 3 | Predictors of neuromyths.

	B (SE)	t	p	95% CI for B	
				Lower	Upper
Intercept	0.250 (0.067)	3.73	0.000	0.118	0.382
Country	−0.001 (0.020)	−0.072	0.943	−0.041	0.038
Age	0.002 (0.001)	1.75	0.082	0.000	0.003
Gender	0.030 (0.021)	1.43	0.155	−0.011	0.071
Teacher	−0.024 (0.019)	−1.27	0.206	−0.061	0.013
Read popular science	0.006 (0.024)	0.256	0.798	−0.041	0.053
Read scientific journals	−0.024 (0.026)	−0.940	0.348	−0.075	0.027
In-service training	−0.002 (0.020)	−0.078	0.938	−0.040	0.037
Knowledge (% correct)	0.240 (0.071)	3.39	0.001*	0.100	0.379

*$p < 0.001$.

Table 4 | Predictors of general knowledge.

	B (SE)	t	p	95% CI for B	
				Lower	Upper
Intercept	0.678 (0.046)	14.631	0.000	0.587	0.769
Country	0.044 (0.02)	2.270	0.024*	0.006	0.083
Age	−0.001 (0.001)	−0.688	0.492	−0.002	0.001
Gender	−0.005 (0.021)	−0.238	0.812	−0.046	0.036
Teacher	−0.002 (0.019)	−0.122	0.903	−0.039	0.034
Read popular science	0.067 (0.023)	2.919	0.004**	0.022	0.113
Read scientific journals	0.002 (0.026)	0.065	0.948	−0.049	0.052
In-service training	0.035 (0.019)	1.814	0.071	−0.003	0.073

*$p < 0.05$; **$p < 0.01$.

half of the teachers. The most prevalent myths related to Brain Gym (Brain Gym International, 2011), learning styles, and left brain/right brain learners. The prevalence of the different myths varied between countries. A higher incidence of myths (higher percentage of questions answered incorrectly) was predicted by higher general knowledge of the brain. The average score on general knowledge of the brain was around 70%. A higher number of correct answers on general statements was predicted by reading popular science magazines. Furthermore, general knowledge about the brain was higher among Dutch teachers. Teacher characteristics (age, sex, primary/secondary school teacher) did not predict literacy or belief in neuromyths.

These results validate previously voiced concerns about the proliferation of neuromyths in the field of education (Organisation for Economic Co-operation, and Development, 2002; Goswami, 2006). They emphasize that teachers who are highly interested in brain research are susceptible to neuromyths. This is troublesome, as these teachers in particular may implement wrong brain-based ideas in educational practice. Misconceptions related to brain-based educational programs were most prevalent, as was also found in a previous study with trainee teachers (Howard-Jones et al., 2009). This suggests that these programs have been successfully marketed within schools ever since the "Decade of

the Brain". The prevalence of misconceptions was found to vary across countries. This might be due to differences across countries regarding the marketing of brain-based programs (Pasquinelli, 2012). For instance, in the NL, there is less marketing of these brain-based programs. There were no differences between countries in terms of general knowledge about the brain. This suggests similar familiarity with brain research between teachers from both countries.

The present research showed that knowledge about the brain was higher when teachers read popular science magazines. Teachers who are eager to learn about the brain and its possible applications in the classroom may more often search for information in the popular media. Furthermore, teachers' views on the role of genetics and environment on learning was investigated. In our survey, teachers in both the UK and NL gave considerably greater weight to the environment, with UK teachers attributing only 22% to genetic factors. This is close to the figure of 25% amongst UK trainee teachers surveyed by Howard-Jones et al. (2009). Yet, Walker and Plomin (2005) also surveyed UK teachers and concluded that the perception of their teachers that genetics was at least as important as environment in most areas was in line with research indicating substantial genetic influence on these domains (e.g., Plomin et al., 2001). Differences between the studies might

be related to confusion over the term "environment", as suggested by Howard-Jones et al. (2009). This term can have a range of disparate meanings in education, most of which are narrower than its meaning within the field of genetics, and many of which may not even include the teacher's efforts.

In contrast to our hypothesis and earlier findings by Howard-Jones et al. (2009) in a sample of trainee teachers, we did not find a protective effect of knowledge on belief in myths. Instead, our results showed that belief in neuromyths correlated positively with general knowledge about the brain. It may be that a lot of interest in the brain has served trainees well in developing their general awareness about the brain. However, teachers who have worked in the field of education for a number of years, will have been confronted with more information about the brain and its influence on learning, both correct and incorrect. Apparently, it is difficult for teachers to then differentiate between this correct and incorrect information. This might be attributed to their eagerness to implement knowledge about the brain in educational practice, in combination with a lack of expertise in neuroscience. Although some of the teachers in our sample followed in-service training about the brain, none of them were experts in the field of neuroscience. Experiments by Weisberg have shown that people with some neuroscientific knowledge (people who followed an introductory cognitive neuroscience class) were fooled by neuroscientific explanations in the same way as laypeople. Only neuroscience experts (defined as people who were about to pursue or had a degree in cognitive neuroscience or related areas) were able to correctly identify non-sense neuroscientific findings. Thus, the level of knowledge of teachers in our sample was not sufficient to protect them against the general credibility of neuroscience findings. When teachers are eager to implement neuroscientific findings, but lack expertise in neuroscience and seek quick and easy solutions, they may fail to recognize misconceptions.

Besides the fact that it wastes money, time, and effort, the implementation of myths in the classroom should be prevented because it may diminish teachers' confidence in a successful collaboration between the fields of neuroscience and education (Sylvan and Christodoulou, 2010; Pasquinelli, 2012). To reduce the number of myths that currently proliferate within schools, we would welcome explicit education for teachers about neuromyths and the lack of scientific evidence for many "brain-based" programs. Previous research has shown that this can be effective in reducing the incidence of misconceptions (Kowalski and Taylor, 2009; Dommett et al., 2011).

To avoid the occurrence of misconceptions in the future, we suggest improving the communication between scientists and practitioners, in addition to enhancing the neuroscience literacy of teachers. Incorporating neuroscience courses into initial teacher training could enhance neuroscience literacy among teachers. In addition, initial teacher training should include the skills needed to evaluate scientific research (Lilienfeld et al., 2012). This would

enable teachers to develop a critical attitude toward the information they receive and examine scientific evidence before including neuroscientific findings into their teaching practice (Howard-Jones, 2009). At the same time, scientists are advised to check translations of their research for the popular media carefully. They should clearly explain what can and what cannot be concluded from their data (Beck, 2010). As some familiarity with brain research was not enough to distinguish myths from the truth, the present study highlights the importance of a dialog between teachers and neuroscience experts in order to establish effective collaborations between the two fields (Jolles et al., 2005; Hruby, 2012). As Dommett et al. (2011) showed, a possible framework for how this could be achieved is to let teachers decide on the topics of neuroscience workshops and to spend considerable time on dialog between neuroscientists and teachers to reflect on the translation of this knowledge to classroom practices.

The present results reflect the prevalence of neuromyths in a sample of teachers with a strong interest in the neuroscience of learning. This yields important information about teachers who may implement wrong brain-based ideas in educational practice. However, average scores on general knowledge and myth assertions may be somewhat different in the population of teachers as a whole. Teachers who are less interested in brain research may believe even more myths, due to a lack of knowledge about neuroscience and a lack of motivation to unravel difficult findings from brain research. For future research, it is important to examine where teachers' incorrect ideas originate (e.g., books, colleagues, commercial companies) and to perform intervention studies directed at increasing teacher competence in understanding the functioning of the brain. Such intervention studies should be performed according to the principles and approach of evidence-based or evidence-informed practice. This could yield valuable information for the prevention of myths in the future and for the development of valid educational innovations.

In conclusion, this research suggests that teachers who are enthusiastic about the possible application of neuroscience findings in the classroom, often find it challenging to distinguish pseudoscience from scientific facts. Possessing greater general knowledge about the brain does not appear to protect teachers from picking up neuromyths. This demonstrates the need to enhance teacher professionalism and interdisciplinary communication to reduce such misunderstandings in the future. It is encouraging that teachers are eager to learn about the brain and its role in learning. Although the integration of neuroscience in educational practice remains challenging, joint efforts of scientists and practitioners may pave the way toward a successful collaboration between the two fields.

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APPENDIX

1. We use our brains 24 h a day (C).
2. *Children must acquire their native language before a second language is learned. If they do not do so neither language will be fully acquired (I).*
3. Boys have bigger brains than girls (C).
4. *If pupils do not drink sufficient amounts of water (=6–8 glasses a day) their brains shrink (I).*
5. *It has been scientifically proven that fatty acid supplements (omega-3 and omega-6) have a positive effect on academic achievement (I).*
6. When a brain region is damaged other parts of the brain can take up its function (C).
7. *We only use 10% of our brain (I).*
8. The left and right hemisphere of the brain always work together (C).
9. *Differences in hemispheric dominance (left brain, right brain) can help explain individual differences amongst learners (I).*
10. The brains of boys and girls develop at the same rate (I).
11. Brain development has finished by the time children reach secondary school (I).
12. *There are critical periods in childhood after which certain things can no longer be learned (I).*
13. Information is stored in the brain in a network of cells distributed throughout the brain.
14. Learning is not due to the addition of new cells to the brain (C).
15. *Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual, kinesthetic) (I).*
16. Learning occurs through modification of the brains' neural connections (C).
17. Academic achievement can be affected by skipping breakfast (C).
18. Normal development of the human brain involves the birth and death of brain cells (C).
19. Mental capacity is hereditary and cannot be changed by the environment or experience (I).
20. Vigorous exercise can improve mental function (C).
21. *Environments that are rich in stimulus improve the brains of pre-school children (I).*
22. *Children are less attentive after consuming sugary drinks and/or snacks (I).*
23. Circadian rhythms ("body-clock") shift during adolescence, causing pupils to be tired during the first lessons of the school day (C).
24. *Regular drinking of caffeinated drinks reduces alertness (C).*
25. *Exercises that rehearse co-ordination of motor-perception skills can improve literacy skills (I).*
26. *Extended rehearsal of some mental processes can change the shape and structure of some parts of the brain (C).*
27. *Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic) (C).*
28. *Learning problems associated with developmental differences in brain function cannot be remediated by education (I).*
29. Production of new connections in the brain can continue into old age (C).
30. *Short bouts of co-ordination exercises can improve integration of left and right hemispheric brain function (I).*
31. There are sensitive periods in childhood when it's easier to learn things (C).
32. When we sleep, the brain shuts down (I).

    Neuromyth assertions are presented in *italic*; C = correct; I = incorrect.

Subjective sleepiness and sleep quality in adolescents are related to objective and subjective measures of school performance

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This study investigated the relation between sleep and school performance in a large sample of 561 adolescents aged 11–18 years. Three subjective measures of sleep were used: sleepiness, sleep quality, and sleep duration. They were compared to three measures of school performance: objective school grades, self-reported school performance, and parent-reported school performance. Sleepiness – "*I feel sleepy during the first hours at school*" – appeared to predict both school grades and self-reported school performance. Sleep quality on the other hand – as a measure of (un)interrupted sleep and/or problems falling asleep or waking up – predicted parent-reported school performance. Self- and parent-reported school performance correlated only moderately with school grades. So it turns out that the measures used to measure either sleep or school performance impacts whether or not a relation is found. Further research on sleep and school performance should take this into account. The findings do underscore the notion that sleep in adolescence can be important for learning. They are compatible with the hypothesis that a reduced sleep quality can give rise to sleepiness in the first hours at school which results in lower school performance. This notion could have applied value in counseling adolescents and their parents in changing adolescents' sleep behavior.

Keywords: sleep duration, sleep quality, sleepiness, school achievement, self-report, parent-report

INTRODUCTION

At the start of adolescence, major changes in sleep behavior take place. Young adolescents go to bed later than children, primarily due to a biologically driven shift in circadian rhythms. Concurrently, sleep behavior is influenced by changes in external factors, which act as "Zeitgebers". The time at which classes start, can be an external influence forcing adolescents to wake up early on school days. The combination of late bedtimes and early rise times leads to the buildup of sleep debt during the school week (Crowley et al., 2007).

The changes in sleep behavior can have a negative effect on school performance, as shown recently in a meta-analysis by Dewald et al. (2010). Sleepiness had the strongest relationship with (inferior) school performance, followed by sleep quality and sleep duration. In their discussion, the authors state that it is unclear whether the relationship between these sleep measures and school performance depends on the indicator of school performance used. The use of objective school performance measures, such as school grades, may lead to different results than the use of self- or parent-reported school performance measures. This obscures our current understanding of relations between sleep duration, sleepiness, and sleep quality and their respective effects on performance (Dewald et al., 2010). The present study therefore investigated how subjective measures of sleepiness, sleep quality, and sleep duration relate to objective, self-, and parent-reported measures of school performance, respectively.

The major advantages of school grades as an objective measure of school performance are their high ecological validity and their reliability due to multiple measurements (Wolfson et al., 2003). However, it is often more practical and cost-effective for sleep researchers to collect data on school performance with a short questionnaire for the student or parent. Different types of self-report and parent-report questions have been used to measure school performance. Some studies used self-reported grade point average (GPA; Eliasson et al., 2002), while others asked students to indicate the level of their grades with answer options such as "mostly A's and B's" (Warner et al., 2008), or with a five-point scale from "far below average" to "far above average" (Maguin and Loeber, 1996).

A meta-analysis showed that self-reported grades differ only slightly from grades delivered by school administrations (Kuncel et al., 2005). When school performance is measured with a more global self-report measure such as a five-point scale, it becomes more likely that the estimation is influenced by factors such as self-esteem or peer comparison. Or, in the case of parent-reports, by how much information parents have about their child's performance. The influence of these factors is not random:

both adolescents and their parents tend to overestimate school performance (Maguin and Loeber, 1996; Kuncel et al., 2005).

Although self-reported and parent-reported school performance are not the same as school grades, they may theoretically have better construct validity than school grades (Kuncel et al., 2005). In some instances, a salient variable is more strongly related to self-reported school performance than to school grades. For example, Huang et al. (2006) found that measures of obesity were related to self-reported school performance, but not to GPA.

No studies have yet compared the relationship between sleep variables and different measures of school performance. For example, subjective "sleepiness" during the first hours at school is a totally different aspect of sleep than a student's self-report "I have trouble falling asleep because many things cross my mind" or "I have difficulty waking up because I am deeply asleep when my mom urges me to get up." In the present paper, three subjective measures are used, namely "sleepiness," "sleep quality" as a measure of a more or less optimal sleep, and "sleep duration." The study investigated the relation between these three measures and school performance in a large sample of 561 adolescents. The relationship between sleep variables and the following measures of school performance was evaluated: (1) self-reported school performance, (2) parent-reported school performance, and (3) end-of-term school grades acquired through the schools' administrations. We hypothesized that sleepiness, sleep quality, and sleep duration would explain school performance, with sleepiness showing the largest effect size, followed by sleep quality and sleep duration. We further hypothesized that the relation between sleep variables and self- or parent-reported school performance would be different from the relation between sleep variables and school grades. The study is of potential relevance for use in school settings because of the evidence that sleep problems and inferior school performance are related. Clarification of the relation between sleep variables and school performance variables can be important in the process of counseling the student and parents as to changing the sleep behavior of the student.

MATERIALS AND METHODS
PARTICIPANTS
In total, 561 adolescents participated, 243 boys and 318 girls (age $M = 14.86$ years, SD $= 1.63$, range $= 11.83–18.95$). They were in grade 7–12 of four secondary schools in the south of the Netherlands. All students followed one of the two advanced educational tracks in Dutch secondary education: higher general secondary education (42.8%) and the more difficult pre-university education (57.2%). Approximately 40% of all students in Dutch secondary education are in these two tracks (Ministry of Education, Culture, and Science, 2009). Level of parental education (LPE), the highest education level of the two parents, was between low and medium in 34.0% (at most a junior vocational education) and high in 66.0% (a senior vocational or academic education). Adolescents were excluded if they had repeated or skipped a grade after kindergarten ($n = 89$), or when data on sleep behavior or school performance were missing ($n = 97$). Participation was voluntary. Participants and their parents gave permission for participation. The Ethical Committee of VU University Amsterdam approved the research protocol.

PROCEDURE
The study had a cross-sectional design, and was part of a larger research project including multiple research questions. Approximately 2000 students received an information letter about the project, of whom 38% were willing to participate. Parents of participants returned a completed questionnaire on demographics and their child's development and behavior. Participants filled in the questionnaires in the classroom, which took approximately 40 min. The questions for this study took approximately 5 min.

MEASURES
Sleep
Sleepiness was measured by putting the following proposition to the adolescents: *I feel sleepy during the first hours at school.* Sleep quality was measured with a sum score based on four questions, which refer to distinct processes affecting sleep quality: *1. I regularly have trouble falling asleep. 2. I often wake up at night and have trouble falling asleep again. 3. I often wake up early and have trouble falling asleep again. 4. I have trouble waking up in the morning. When the alarm clock rings, I have trouble getting up.* Answers were given on a five-point Likert scale ranging from "totally agree" (five points) to "totally disagree" (one point). Sleep duration was measured by asking parents the following questions, both for school days and weekends/holidays: *What time does your child usually go to bed? What time does your child usually wake up?* Answers were in hours and minutes. Based on these bed and rise times, two sleep duration measures were calculated: time in bed (TIB) school days and TIB non-school days.

School performance
Objective school performance was measured with end-of-term grades (ranging from 1.0 – very bad – to 10.0 – outstanding) of the school year in which the study was carried out. The grades were acquired through the schools' administration. School performance was measured with the mean of the subjects' Dutch (native language), mathematics, and English as a foreign language (Reed et al., 2010). Because the schools in the sample used different grading policies, we assumed that the grades would not be comparable. Therefore, each school's grades were transformed into *z*-scores based on the schools' mean grade and standard deviation. Thus, academic performance was measured with the standardized mean grade for Dutch, mathematics, and English.

Self-reported subjective school performance was measured by asking adolescents the question: *How do you perform at school, compared to your classmates?* Parents answered this question about their child. Three answer options were given: "insufficient", "average", and "above average".

ANALYSES
To investigate the relationship between measures of sleepiness, sleep quality, sleep duration, and objective school performance, a hierarchical multiple regression analysis was performed with standardized mean grades as outcome measure. The first block consisted of the background variables age, sex, educational track, and LPE; in the second block the sleep measures were

added. Similar logistic regression analyses were performed with dichotomized self-reported and parent-reported school performance. To dichotomize the scores, the "insufficient" category was dropped, because it contained less than 5% of the total sample. Thus, $n = 537$ in the logistic regression analyses with dichotomized scores consisting of the answers "average" versus "above average". In all other analyses, $n = 561$.

RESULTS

Table 1 shows descriptive statistics of sleep and school performance measures. The measures of sleepiness, sleep quality, TIB on school days, and TIB on non-school days correlated between $r = 0.00$ (sleep quality and TIB on non-school days) and $r = 0.34$ (sleepiness and sleep quality, which is significant

at the $p < 0.01$ level). Self-reported school performance and parent-reported school performance correlated highly ($r = 0.66$), and had good agreement, with kappa $= 0.65$. Both scores were $r = 0.50$ correlated to school grades, with an intraclass correlation coefficient (ICC) $= 0.38$ for self-reported scores and ICC $= 0.40$ for parent-reported scores. These are moderate effects, and similar for adolescents and parents, which indicate that adolescents and parents are equally good at estimating school performance.

Table 2 shows results of linear and logistic regression analyses. Significant predictors differed for the three school performance measures. School grades were predicted by sex, education track, LPE, and sleepiness. This means that girls, students from pre-university education, and students with highly educated parents achieved the highest school grades. In addition, sleepy students achieved lower grades than their peers. Sleep quality and sleep duration were not related to school grades.

Self-reported school performance was significantly related to sleepiness only, with sleepy students reporting lower performance than their peers. None of the associations with background variables or other sleep variables were significant. Parent-reported school performance was predicted by sex, education track, and sleep quality. According to parents, girls, students from pre-university education, and those with good sleep quality had higher school performance than their peers.

DISCUSSION

The current study investigates several subjective measures of sleep, and both objective and subjective measures of school performance in adolescents. The study was set up to evaluate the hypothesis that the measures used might determine whether or not a relation is found between sleep and school performance. The findings show

Table 1 | Descriptive statistics of sleep and school performance.

Variables	
Sleepiness, M (SD)	2.38 (1.13)
Sleep quality M (SD)	9.34 (3.01)
TIB school days (*hh:mm*), M (SD)	9:03 (00:40)
TIB non-school days (*hh:mm*), M (SD)	10:25 (01:01)
Standardized school grades, M (SD)	0.00 (1.00)
Self-reported school performance	
Insufficient	4.3%
Average	57.4%
Above average	38.3%
Parent-reported school performance	
Insufficient	4.3%
Average	53.5%
Above average	42.2%

Table 2 | Relations between sleep and school performance measures: results of linear and logistic regression analyses.

Predictors	Standardized mean grades[a]	Self-reported school performance[b]	Parent-reported school performance[b]
	Beta	Exp(B)	Exp(B)
Block 1	$R^2 = 0.12$	Cox & Snell $R^2 = 0.01$	Cox & Snell $R^2 = 0.06$
Age	−0.03	0.98	1.03
Sex	0.15**	1.20	1.66**
Education track	0.28**	1.42	2.36**
LPE	0.09*	1.26	1.12
Block 2	$R^2 = 0.13$	Cox & Snell $R^2 = 0.06$)	Cox & Snell $R^2 = 0.09$
Age	−0.04	1.06	1.08
Sex	0.16**	1.31	1.86**
Education track	0.27**	1.42	2.43**
LPE	0.08*	1.21	1.06
Sleepiness	−0.12**	0.77**	0.92
Sleep quality	−0.02	0.95	0.91**
TIB school days	−0.03	1.35	1.31
TIB non-school days	−0.05	0.84	0.84

LPE, level of parental education; TIB, time in bed.

[a]*Linear regression analyses, N = 561;* [b]*logistic regression analyses, N = 537.*

*p < 0.05, **p < 0.01.

that this is indeed the case; the implication is therefore that further research on sleep and school performance should take the important question "what do we measure and what does it refer to?" into account. The measure "sleepiness" gives an indication of reduced alertness and attention during the first hours at school. This measure was used because of the fact that many adolescents have complaints of distractedness and attentional problems especially in the first hours at school. Indications exist that such problems and subjective sleepiness might be related to more or less disturbed sleep. Research has shown that a shift occurs in the 24 h diurnal rhythm in young adolescents. This can have as a result that the student goes to bed at a later moment than in his childhood. And this causes a difficulty in getting up. The student may in fact have a shorter night than is optimal for proper functioning during the school day: the restorative function of sleep might therefore be compromised. The findings in this study indeed show that sleepiness in the first hours at school is correlated both to lower school grades and to lower self-reported school performance. A different finding was done for the second sleep measure, namely "sleep quality." This measure gives an indication that the student has difficulty falling asleep, has trouble waking up and/or wakes up at night, and has trouble falling asleep again. This second measure appeared to be related to parent-reported (but not student-reported) school performance. No relation was found to school grades. The third measure (the duration of the sleep as reported by parents) was not related to any of the school performance measures. Therefore, the fact that previous studies did not always find expected relations between sleep and school performance (see Dewald et al., 2010) may be due to the use of different school performance measures. In future studies, it is of major importance to carefully choose the relevant measure. The findings done in the present study underscore the notion that sleep is important for performance at school in adolescents. An implication is that school performance could be improved by creating the conditions in which the students is less sleepy, more alert, and also has a better sleep quality. As the present study was set up as a large scale epidemiological study, future studies must go in depth with respect to more carefully defining and measuring sleepiness and sleep quality, and also evaluating individual students at more time points over the day and even through the week. This type of studies is presently underway.

With respect to the measurement of subjective school performance reported by adolescents and by parents, a methodological remark has to be made. The student and the parent-reports seemed quite similar at first sight: they were both moderately good in estimating school performance. However, self- and parent-reported

school performances do appear to measure different concepts: parent-reported school performance was related to sex and educational track, while student-reported school performance was not. This must be due to differences between students and their parents in the evaluation of school performance and in the comparison group used. Adolescents probably compare themselves with peers who are very similar to them, are of the same sex, and from the same educational track. That is their frame of reference. Besides, the students will have a different opinion as to what constitutes "appropriate school performance" in comparison to their parents. The parents can be expected to evaluate the performance of their children with a broader reference group and against more abstract norms. Future research should clarify this issue by acquiring more information about the reference group used by adolescents and parents and on the attitudes with respect to what they consider as appropriate school performance.

The current study illustrates that self-reported school performance, parent-reported school performance, and school grades do not measure the same construct. To understand more of the complex relations between the various sleep measures and their effects on school performance, differences between school performance measures should be included in future studies. Accordingly, they should choose a school performance measure that best fits their research question. Furthermore, to avoid confusion, it would be helpful to mention explicitly which measure is used, for example by speaking about "self-reported school performance" or "objective school performance".

There are implications of the study for school practice and for education in a broad sense. The finding that sleepiness correlates to performance can be used in counseling the student and his or her parents. A first step is to acknowledge the fact that sleepiness can be due to problems falling asleep or waking up or other aspects of sleep behavior. The student and his or her parents can acquire insight as to the factors which improve the risk for sleepiness. This gives the student more control over his sleep behavior and help him to seek guidance or "tips" in creating the conditions which lead to better sleep and decreasing fatigue at school. More attention for the subjects taught at school could lead to better school grades and also more motivation to learn and perform. All in all: it can show both student, teacher and parents that performance at school is the result of more than only didactical procedures, and that biological factors can also be of major importance . . . and that the student and his or her parents can learn to create the conditions at home which have positive impact on functioning at school.

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Neuroscientific model of motivational process

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Considering the neuroscientific findings on reward, learning, value, decision-making, and cognitive control, motivation can be parsed into three sub processes, a process of generating motivation, a process of maintaining motivation, and a process of regulating motivation. I propose a tentative neuroscientific model of motivational processes which consists of three distinct but continuous sub processes, namely reward-driven approach, value-based decision-making, and goal-directed control. Reward-driven approach is the process in which motivation is generated by reward anticipation and selective approach behaviors toward reward. This process recruits the ventral striatum (reward area) in which basic stimulus-action association is formed, and is classified as an automatic motivation to which relatively less attention is assigned. By contrast, value-based decision-making is the process of evaluating various outcomes of actions, learning through positive prediction error, and calculating the value continuously. The striatum and the orbitofrontal cortex (valuation area) play crucial roles in sustaining motivation. Lastly, the goal-directed control is the process of regulating motivation through cognitive control to achieve goals. This consciously controlled motivation is associated with higher-level cognitive functions such as planning, retaining the goal, monitoring the performance, and regulating action. The anterior cingulate cortex (attention area) and the dorsolateral prefrontal cortex (cognitive control area) are the main neural circuits related to regulation of motivation. These three sub processes interact with each other by sending reward prediction error signals through dopaminergic pathway from the striatum and to the prefrontal cortex. The neuroscientific model of motivational process suggests several educational implications with regard to the generation, maintenance, and regulation of motivation to learn in the learning environment.

Keywords: motivation, neuroeducation, educational neuroscience, reward, value, goal, decision-making, self-regulation

INTRODUCTION

Since early theories of biological motives such as hunger, thirst, and sex have been proposed, research on diverse aspects of human motivation has been conducted to extend its conceptual boundaries and understand the dynamics of motivation. As a result, we have major psychological theories on motivation including reinforcement learning theory, need theory, attribution theory, self-efficacy theory, self-determination theory, expectancy-value theory, achievement goal theory, interest theory, and self-regulation theory. There is no doubt that these theories have contributed in deepening our understanding of complex human motivation, but it's time for a new approach to overcome the fundamental limitation of traditional theories.

Existing theories on motivation bear three limitations. First is the vagueness of the concept of motivation. It is practically impossible to draw a clear line between motivation and other concepts such as drive, need, intention, desire, goal, value, and volition. Due to this conceptual vagueness, it is difficult to come to a consensus on whether motivation refers to an psychological state or process, let alone the definition. Various constructs in different theories of motivation are overlapping and often create confusion. For instance, the vague conceptual distinctions between intrinsic motivation and interest, self-efficacy and perceived competence, value and reward, self-regulation and volition hinder effective

communication and constructive arguments on the identical phenomenon of motivation.

Second limitation is the absence of comprehensive theory on motivation. Although a number of theories on motivation have been proposed, each one deals with only a specific fraction and it lacks profound understanding of motivational process as a whole. The measurement of motivation is the third limitation. Action selection, frequency and persistence of the action, and the degree of time and effort put into sustaining the action are direct indicators of motivation. Although these measurements can be obtained objectively through a long-term observation, due to practical limitations, they are mostly conducted in the form of self-report surveys on psychological constructs that are highly correlated with behavioral measurement. However, as motivation is largely implicit and dynamic, the measurement relying on self-report is very much restricted to consciously accessible aspect of motivation.

Due to these limitations, extensive research on motivation so far is yet to provide practical implementation into schools or workplaces. For effective motivational interventions, we need to set a clear conceptual definition of motivation and come up with a comprehensive conceptual framework that integrates diverse perspectives. Measuring the brain activation pattern using neuroimaging techniques can be a complementary way of overcoming

above-mentioned limitations. By detecting the changes in the brain during task performance, it became possible to understand the dynamic yet implicit nature of motivation.

I propose a tentative model of motivational processes which focuses on the various stages of being motivated, based on converging evidence in cognitive neuroscience, affective neuroscience, social neuroscience, developmental neuroscience, and neuroeconomics. In order to fully understand a phenomenon, it can take more than a single unit of analysis which determines the level of explanation. The more converging evidence from diverse levels of explanation are provided, the more precise the understanding of the phenomenon it becomes. The same goes for motivation. Diverse units of analysis and levels of explanation coexist; from microscopic molecular perspective to macroscopic socio-cultural perspective. As shown in **Figure 1**, the unit of analysis draws the distinction among different levels of explanation: neuronal level, psychological level, and behavioral level.

The neuronal level of explanation describes the motivation-related phenomena as functions of the ventral striatum involved in reinforcement learning, the orbitofrontal cortex (OFC) region linked to value judgment and decision-making, and the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (DLPFC) regions associated with executive function and cognitive control. On the other hand, the units of analysis in the behavioral level of explanation refer to the frequency and persistency of the action, the degree of effort and engagement, selection of approach and avoidance behavior, regulatory behavior, and so on. The psychological level of explanation has mainly considered

constructs such as reward, expectation, value, goal, attribution, competence, interest, and self-regulation as the primary units of analysis. However, these are somewhat ambiguous and overlapping psychological constructs which may not correspond to units of analysis in the neuronal level. With the rapid advance in the field of neuroscience, the validity and conceptual clarity of these psychological constructs can be complemented by neuroscientific evidence, and thereby the fundamental reconceptualization on the psychological level has become active (e.g., Rangel et al., 2008; Heatherton, 2011).

In this paper, I focused on pleasure, value, and goal as principal units of analysis on psychological level because their underlying neural mechanisms have been heavily investigated and relatively well identified. I also try to propose a neuroscientific model of motivational processes in which motivation is regarded as a dynamic process and is understood as a series of detailed sub processes of generation, maintenance, and regulation of motivation. I will explain the generation of motivation in terms of the reward-driven approach process, the maintenance of motivation in terms of the value-based decision-making process, and the regulation of motivation in terms of goal-directed control process (See **Figure 2**).

GENERATION OF MOTIVATION: REWARD-DRIVEN APPROACH PROCESS
ROLE OF REWARD
One of the most powerful variables influencing motivation is reward, irrespective of reward type (physical or social reward).

FIGURE 1 | Levels of explanation and units of analysis on motivation.
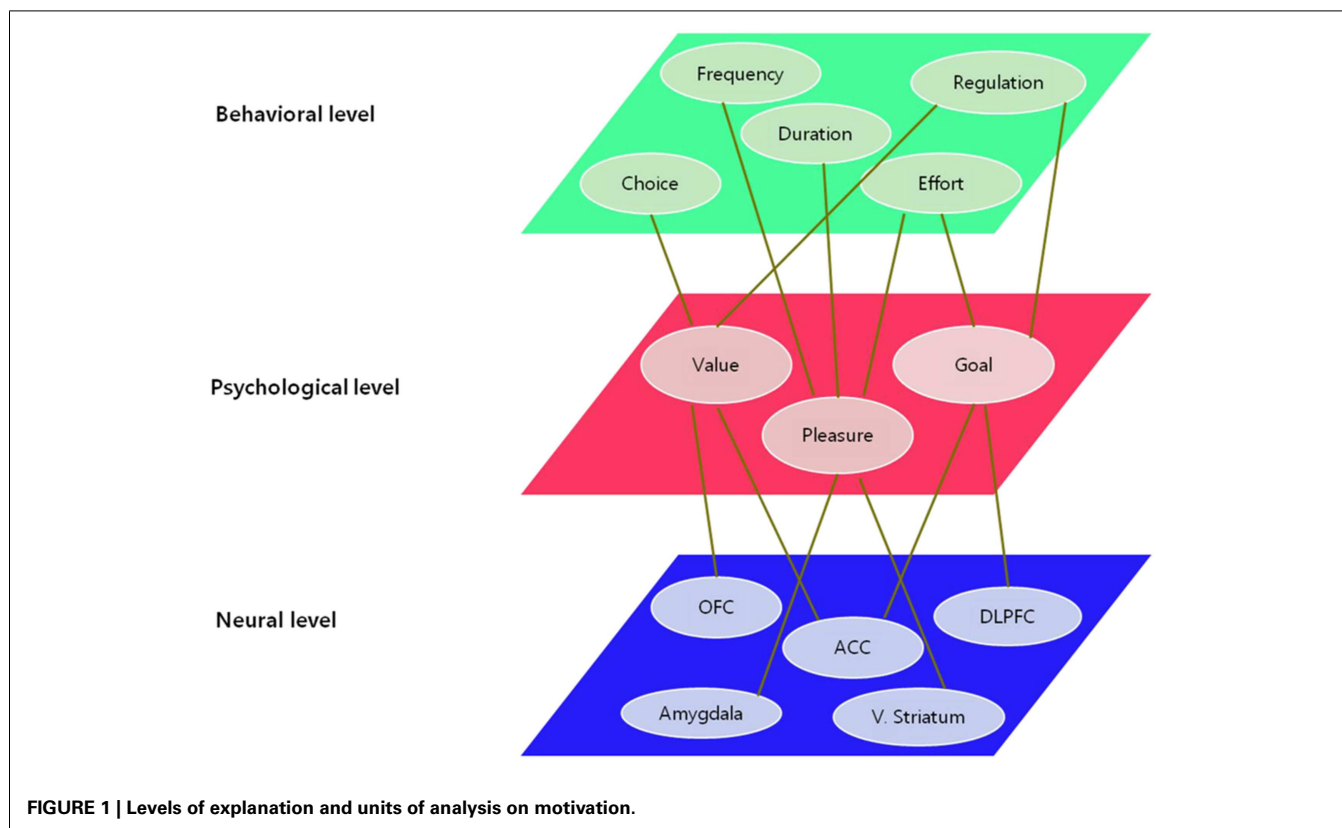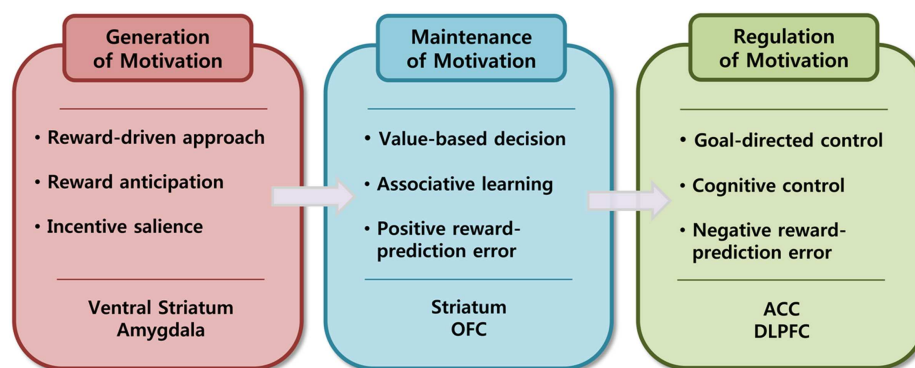
FIGURE 2 | Three sub proceses of motivational process.

The main function of reward is to induce positive emotions, make the organism approach, increase the frequency of the target behavior, and hence prevent extinction (Schultz, 2004). As a result, the organism looks for predictive reward signals, acquires the stimulus-reward association, encodes the value of reward, and decides on approach or avoidance behavior to acquire the sustainable reward. However, the reward mechanism is not simple when the associative learning via reward, reward-based decision-making, and behavioral control to obtain future reward are taken into account. The reward processing consists of a sequence of sub processes such as anticipating the reward, associating reward with behavior, planning to obtain the reward, encoding the value of reward, and updating the relative value of reward. Thus, diverse brain regions are recruited during reward processing.

The primary brain regions associated with reward is the dopamine pathway widely known as reward pathway. Dopamine is a neurotransmitter that is produced in the ventral tegmental area (VTA), passes through the globus pallidus and released into the nucleus accumbens (NAcc) located in the striatum (See **Figure 3**). This pathway is divided into mesolimbic dopamine system and mesocortical dopamine system. Mesolimbic dopamine system is where VTA neurons are connected to the NAcc, the septum, the amygdala, and the hippocampus; and mesocortical dopamine system is the linkage between the medial prefrontal cortex (MPFC), the ACC, and the perirhinal cortex. The mesolimbic dopamine system is responsible for reward anticipation and learning, whereas the mesocortical dopamine system involves in encoding the relative value of the reward and goal-directed behavior.

The OFC, the amygdala, and the NAcc are the brain regions that are consistently reported to be involved in reward processing (e.g., Haber and Knutson, 2010). The DLPFC, the MPFC, and the ACC are also reported to be relevant to reward processing, but the primary functions of these areas are more to do with the executive function in achieving the goal (Miller and Cohen, 2001; Walter et al., 2005). The OFC-amygdala-NAcc system responds not only to primary rewards such as food or sexual excitement but to secondary rewards like money and social rewards including verbal praise or cooperation (Rilling et al., 2002; Kringelbach et al., 2003; Izuma et al., 2008). In particular, the NAcc known as the

pleasure center is activated when a variety of rewards are anticipated or received. For instance, the NAcc is activated when people were presented with favorite stimulus, engaged in favored activity, smoking, hearing jokes, and even when feeling love (Aharon et al., 2001; Mobbs et al., 2003; Aron et al., 2005). In contrast, several studies show that amygdala, which is known to respond to conditions associated with fear and negative stimulus, is intensity-sensitive not valence-sensitive (Anderson et al., 2003; Small et al., 2003).

In case of primary reward, which is essential for survival that all the species are automatically programmed to approach it, the ventral striatum including the NAcc forms an association of behavior-outcome. However, in case of conditioned secondary reward, the OFC encodes and represents the associative value of reward, and updates the value for future decision-making process. The OFC is the critical brain region for value judgment (Grabenhorst and Rolls, 2011). In particular, the medial OFC is reward-sensitive, whereas the lateral OFC is punishment-sensitive (O'Doherty et al., 2003). Tremblay and Schultz (1999) have discovered that the OFC does not respond to the absolute value of the reward but it calculates the relative value of the reward and respond only to the ones with higher preference. This finding is in line with Premack's principle which states that reward is highly subjective and relative and suggests that there is no such thing as universal reward which goes beyond the individual characteristics and specificity of the situation.

Social neuroscience research has discovered that both social and physical rewards/punishments activate the same area of the brain (Lieberman and Eisenberger, 2009). In other words, social rewards such as reputation, fairness, cooperation, and altruistic behavior activate the reward-related network that is activated when experiencing physical pleasure. Social aversive stimuli such as social exclusion, unfair treatment, and social comparison activate the pain-related brain regions. These results suggest that social reinforcement and punishment are as powerful and effective as physical reward and pain. It is important to conduct neuroeducational studies to investigate whether social stimuli such as compliment, encouragement, support, empathy, cooperation, fairness, and altruistic behavior activate the reward pathways of children and adolescents, and to design a learning environment
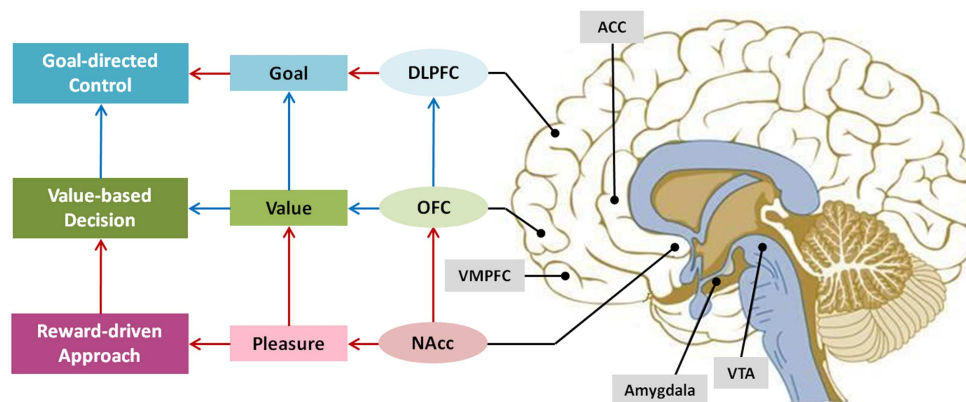
FIGURE 3 | Key brain regions related to motivational process.

that allows sustainable activation of reward pathways. Based on these findings on how bullying, normative grading, competition, discrimination, punishment, and penalty systems at schools are affecting the students' brain development, we can suggest possible solutions to minimize these demotivating features of the learning environment. Kim et al. (2010), for example, conducted a study where learners were given feedback on their performance in the form of absolute assessment and relative assessment, and their brain activation patterns were compared during feedback. The result showed that when relative assessment was given to low competence learners, the amygdala, a brain region associated with negative emotions, was activated even if the feedback valence was not negative. This suggests that relative assessment should be used with caution, especially for learners with low competence, because it produces negative affect regardless of their actual performance.

One important issue in relation to reward is the distinction between intrinsic and extrinsic motivation. If intrinsic and extrinsic motivation are different constructs, is it possible to biologically distinguish them and find dissociable neural mechanisms underlying each type of motivation? No neuroscientific evidence has yet been found to support this claim. Moreover, it is quite common that extrinsic and intrinsic value for a specific behavior coexists. Since each reward has specific value which is subjectively computed, whether the source of the value is internal or external may not carry any significant meaning in value computation process.

People are motivated to behave to obtain desirable outcomes, and also to avoid negative consequences. But under rapidly changing circumstances where the consequence of the action is uncertain, a decision has to be made whether to stick to one's current strategy or to look for new alternatives. The trade-off between these two options is known as exploration-exploitation dilemma in reinforcement learning (Sutton and Barto, 1998). In exploratory learning where new alternatives are sought, both the frontopolar cortex and the intraparietal sulcus responsible for value judgment and inference are activated (Daw et al., 2006). On the other hand, in exploitative learning where habitual decision-making occurs based on prior experience, the striatum and the MPFC are activated. That is, the striatum and the amygdala are responsible for approach and avoidance behavior respectively which

are modulated by the prefrontal cortex. According to the studies on brain development, the NAcc which is sensitive to reward shows rapid development in adolescence, whereas the amygdala that plays a key role in avoidance of danger shows rather slow development, and the prefrontal cortex responsible for controlling of action shows the slowest development (Ernst et al., 2005; Casey et al., 2008). Therefore, adolescents are likely to demonstrate behavioral tendencies that are more close to exploitation than exploration. This imbalance between limbic system and prefrontal cortex in adolescent brain development provides an understanding of impulsive, sensation-seeking, and risk-taking behaviors of teenagers.

In the study on the sensitivity to reward, adolescents showed greater activation in the NAcc while receiving the reward than adults (Galvan et al., 2006; Ernst and Frudge, 2009), but the opposite pattern was true while anticipating the reward (Bjork et al., 2004). Additionally, in the adult brain, the OFC was activated when the expected reward was not given (Van Leijenhorst et al., 2010). This suggests that existing value system of the adult is probably being updated to pursue successive rewards when the expected reward is not given. Adolescents are known to be more sensitive to rewards or positive feedback but less to punishments or negative feedback than adults (Bjork et al., 2004). The comparison of brain activation by age groups showed the differential activation pattern in the DLPFC. For the children aged 8–9, it was activated when positive feedback was given, whereas for children aged 11–13 it was activated in response to both positive and negative feedbacks. For adults aged 18–25, it was activated only when negative feedback was given (Duijvenvoorde et al., 2008). This developmental difference suggests that negative feedback for young children might not be effective due to the slow development of the prefrontal cortex.

DISTINCTION BETWEEN LIKING AND WANTING
The intrinsically motivated activity does not necessarily accompany hedonic enjoyment. For example, although a soccer player may have a strong intrinsic motivation to play soccer, sometimes he may not feel pleasure during physical training or soccer practice. Spontaneous goal-directed actions are inherently motivated, but instrumental actions to achieve a goal can be temporarily

unpleasant. The new contention that pleasure and enjoyment are not sufficient conditions for intrinsic motivation has been gaining recognition. According to Berridge (2007), positive emotions and intrinsic motivation do not coincide all the time and they are operated by different physiological mechanisms. In other words, the persistent approach behavior toward a specific stimulus does not necessarily mean that the stimulus is favored. Berridge and Robinson (2003) suggested that reward has two values; hedonic value reflecting the degree of liking and incentive value reflecting the degree of wanting. Whereas "liking" is a passive state in which the quality of the stimulus is evaluated after being processed, "wanting" is an active state where stimulus is pursued before being processed. Wanting is not a state of desire like drive or craving, but a process that a specific stimulus embodies attractive value on the sensational or cognitive level. In order to distinguish "wanting" from its commonsensical meaning, it is often referred to as incentive salience.

Olds and Milner (1954) conducted a seminal experiment on the function of NAcc known as the pleasure center using a Skinner box. An electrode connected to a lever was implanted in the NAcc of a rat so that the NAcc was stimulated whenever the rat pressed the lever. They observed that the rat continuously pressed the lever without eating to stimulate the NAcc until it became totally exhausted. As it was impossible to conduct a self-report to verify whether the rat actually liked the electrical stimulation, a new method of measuring the emotion was needed. One widely used method of measuring pleasure or pain in infant or animal studies is to analyze the specific pattern of facial expressions in response to various kinds of taste, which is a universal indicator of emotions across species (Berridge, 2000). An animal study demonstrated that the NAcc of a rat was activated by drugs such as cocaine but its facial affective expression in response to the drugs was a disliking reaction (Berridge and Valenstein, 1991). This may in part explain why drug addicts constantly want the drug but they do not actually like it. Berridge (2003) also revealed that the brain regions responsible for liking and wanting are anatomically separated within the NAcc. These findings support the notion that persistent action to obtain specific stimulus is not necessarily pleasure-seeking one and wanting can occur without liking. By contrast, liking without wanting can be found in a study where the release of dopamine is suppressed by lesions or dopamine antagonists. In this case, no wanting behavior toward reward was shown, but there was no decrease in the degree of liking for the reward (Berridge and Robinson, 2003). Hence, it can be concluded that dopamine plays a key role in wanting the stimulus and increasing incentive salience, but it does not affect the liking for the stimulus.

Theories of intrinsic motivation and interest posit that people are intrinsically motivated to persistently engage in the activity when they experience pleasure and enjoyment (Csikszentmihalyi, 2000; Ryan and Deci, 2000; Hidi and Renninger, 2006). However, if "liking" and "wanting" are dissociated, motivation is not generated by feeling pleasure or liking the activity without wanting or incentive salience. This means that a state of liking for a specific object or activity cannot be understood as a motivational state and that liking is not a prerequisite for generating motivation. From this perspective, liking refers to an emotional state whereas wanting has more to do with motivation and decision utility (Berridge

and Aldridge, 2008). There is a need for careful reconsideration for the argument in which the school activity should be enjoyable to generate motivation because pleasure and enjoyment may not automatically lead to motivation. Hence, the transition from liking to wanting and the relationship between motivation and emotion remain an important issue. Moreover, applying the aversive conditioning to behavior modification, which makes undesirable behavior less attractive, has to be cautiously examined because the assumption that people like their habits may be wrong.

Another new hypothesis about the function of NAcc is that dopamine plays a role in effort-related behaviors. The traditional hypothesis that dopamine is associated with the reward function has recently been criticized. These criticisms are based on the finding that the NAcc dopaminergic system is not involved in the pleasure relevant to the positive reinforcement, but is responsible for behavioral activation and effort-related functions (Salamone et al., 2007). An animal study on the effect of dopamine dosages demonstrated that dopamine depletion caused longer response time and severe deterioration in high-effort task performance. Also, rats with insufficient dopamine are prone to choose tasks requiring less effort over tasks requiring much effort (Salamone et al., 2005). According to these studies, the NAcc dopaminergic system may modulate the effort regulation rather than reward-related function. The brain regions associated with effort-based decision-making include an extensive circuit from the thalamus, the amygdala, and the ACC to the prefrontal cortex, but the NAcc is the key area to interact with these areas.

MAINTENANCE OF MOTIVATION: VALUE-BASED DECISION PROCESS

REWARD PREDICTION ERROR AND LEARNING

No motivation is sustained without learning and memory. Approach-avoidance behaviors are learned and goal-directed behaviors depend on working memory. Because remembering actions that result in positive or negative outcome is beneficial in adaptation, stimulus-action-outcome association is learned and actions become habitual and automatic. Dopamine is known to be mainly associated with reward and pleasure, but it is a neurotransmitter that also plays an important role in motor performance, conditioning, learning, and memory (Wise, 2004). Insufficient dopamine causes stiffness and paralysis seen with patients with Parkinson's disease, whereas excessive dopamine may result in behavioral disorders such as schizophrenia, impulse control disorder, ADHD, and addiction. After being injected with dopamine as treatment for Parkinson's disease, the patients showed a marked increase in the compulsive behaviors such as excessive gambling or eating disorders (Dagher and Robbins, 2009). Functional disorders associated with excessive dopamine are not being able to control the dominant motor response, focusing more on gains than losses, making hasty and risky decisions, favoring small but immediate reward and so on.

According to reinforcement learning theory, the magnitude of learning depends on the dopamine release (Montague et al., 1996). Both positive reinforcement accompanying appetitive stimuli and negative reinforcement removing aversive stimuli increase dopamine release, which in turn increases the frequency of the target behavior and leads to associative learning between stimuli

and behavior. Through repeated association with neutral stimuli (environmental stimulus or psychological state), the powerful association of stimulus-action-outcome is learned. The initial reward for a chosen action is most likely unpredictable, so the effect of the reward is maximized. This difference between the expected and the actual reward is referred to as reward prediction error (RPE), which is encoded by dopaminergic neurons. The larger the RPE is, the more dopamine is released. In a study conducted by Schultz et al. (1997), they examined the response of a single dopamine neuron. At an early stage of learning when the chimpanzee did not expect a reward, dopamine neuron was activated while receiving reward. However, when a reward was always anticipated due to repetition, the dopamine neuron was activated only when cues for the reward were given, and it was not actually activated while receiving the reward. On the contrary, when the expected reward was not given, dopamine neuron was suppressed. This shows clearly that it takes only anticipation for the reward, through various conditioned stimuli associated with reward or punishment, not the reward itself, to boost the dopamine release and hence to generate the target behavior. This is a very beneficial way of learning from the perspective of adaptation.

There are two types of RPE: positive and negative RPE (Schultz, 2006). Positive RPE is generated when the outcome is better-than-expected or unexpected rewards are given, whereas negative RPE is generated when the outcome is worse-than-expected or expected rewards are omitted. The larger the positive RPE, the bigger the surprise, hence maximum learning occurs. Repeated use of rewards, however, increase the expectation of reward at all times reducing positive RPE, so it reaches an asymptote (close to zero) without learning gains. For this reason, the typical learning curves are negatively accelerated, indicating that rapid growth occurs at early stages of learning but this increment gets smaller on later stages.

To maintain students' motivation for target behavior, a certain amount of dopamine should be released during or after the pursuit of the target behavior. The dopamine can be released by the positive RPE whenever the unexpected positive outcomes are given. At this point, a specific action is sustained as long as the outcome of a habitual action is satisfactory. In order to maximize the learning, it is essential to provide relatively new reinforcements to increase positive RPE. It is highly consistent with interest theory which posits the importance of providing the unexpected stimuli which can be easily resolved later, such as novel or surprising stimuli with cognitive gap or conflict (Berlyne, 1974; Kim, 1999). However, one of the dilemmas among educators is that any kind of learning requires practice through repetition which usually undermines the motivation. Thus, if the instructors cannot help but repeat the learning material, then they should introduce a new learning activity or novel learning context in order to produce positive RPE.

The clear example of the motivation-learning link is addiction. Excluding serious malfunctions in controllability, an addicted behavior is not only the most powerfully motivated action but also the result of maximum learning. Once the cue-reward association is learned, the role of the cues to activate the dopamine system grows, but the role of reward itself gets smaller. That is because the brain has a strong tendency to reduce dopamine release when the reward is expected (Self, 2003). However, in the case of psychoactive substances such as alcohol or cocaine, dopamine is excessively released without the typical learning process. As a result, extreme memory or pathological learning is induced to recognize these substances as new and salient rewards (Hyman et al., 2006). This explains why it is difficult to break the drug addiction and why only a single exposure can lead to a relapse even after a long period of abstinence. Behavioral addictions including online game addiction which is common among adolescents, are also reported to show a similar pattern to drug addiction (Grant et al., 2006), but more systematic studies need to be conducted to reveal the precise mechanism.

OUTCOME EVALUATION AND ACTION SELECTION

Numerous behaviors in everyday life are determined by the choice from many other alternatives whether to continue or to stop a specific action. Action selection is a part of decision-making process based on value assessment. The higher the assessed value of the outcome from the selected action, the greater the possibility of choosing it later. Rangel et al. (2008) distinguished three different types of valuation systems which play an essential role in decision-making process; Pavlovian, habitual, and goal-directed system. Pavlovian system assesses values with regards to the salience of stimulus. The network of the amygdala, the NAcc, and the OFC is involved in this process. Habitual system evaluates the value of stimulus-response association following the reward. The dorsal striatum and the cortico-thalamic loops are the main brain regions for this system. Lastly, goal-directed system calculates the association of action-outcome and evaluates the reward assigned to other outcomes. The OFC and the DLPFC are responsible for this process. Let's take studying as an example of value-based decision-making. Pavlovian system assesses the value of a specific school subject such as English, habitual system evaluates the action of studying English vocabulary every morning, and goal-directed system determines which subject to concentrate on during vacation.

To make an effective choice, it is required to judge the potential value of the action which reflects the probability of its desirable outcomes. This is referred to as expected utility in economics and psychology. The brain should calculate the expected value before the choice is actually made. In an experiment where the magnitude and probability of the reward were manipulated, the NAcc activation showed a positive correlation with the magnitude of expected reward and positive emotions, and the activity of the MPFC had a positive correlation with the probability of obtaining the reward (Knutson et al., 2005). This finding indicates that the subcortical structure responds mainly to physical property and emotional aspect of reward, whereas the prefrontal cortex is more involved in the higher order computational function associated with the probability of obtaining the reward. In case where unexpected outcome is resulted from a choice, recomputation or update of the value of the action is required. Hence, children and elderly with low prefrontal cortex function tend to find it difficult (Brand and Markowitch, 2010).

The OFC, a core brain region for value judgment and decision-making, is also known as a reward-related region, but its role in reward processing is not straightforward (Kringelbach, 2005). Animal studies have demonstrated that animals with OFC lesions were

capable of normal reward processing. They were able to perform actions to obtain rewards, learn the associations between stimuli and new rewards, and distinguish rewards from no rewards (Izquierdo et al., 2004; Rudebeck et al., 2006). This indicates that the primary function of OFC is to integrate every aspect of information, calculate the value to expect the outcome of the choice, and represent it in working memory (Montague and Berns, 2002). According to the somatic marker hypothesis by Damasio (1996), somatic states related to various emotions, which were generated during the process of evaluating actions, influence the final decision. The function of OFC in this process is to encode somatic state associated with the environmental pattern and retrieve it to recalculate the value for future decision-making. A neuroimaging study demonstrated that the OFC responded not only to sensory stimuli inducing pleasant-unpleasant odor and sound, but to abstract reward and punishment such as making money and losing it (Rolls and Grabenhorst, 2008). The OFC is in close connection with adjacent prefrontal regions and constantly interacts with them to search for more effective decision-making. More specifically, the OFC calculates the value, whereas the DLPFC retains this information to plan actions for the reward and the MPFC evaluates the effort required to execute the plan (Wallis, 2007; Grabenhorst and Rolls, 2011).

The function of OFC becomes clear when we take a close look at the cases with OFC damage. The most famous case is Phineas Gage who was working as a railroad construction foreman when he was involved in an accident in which a metal rod was driven through his head. He survived the accident and displayed normal cognitive abilities but he exhibited inappropriate behaviors in social interactions such as erratic and impulsive behaviors. This case drew attention as the first case to demonstrate the possible relation between prefrontal cortex including the OFC and social skills or personalities. Patients with OFC damage are not cognitively impaired, but show severe defects in daily decision-making and tend to exhibit obsessive-compulsive disorder, drug or gambling addiction, and eating disorder (Camille et al., 2004). It is also known that patients find it difficult to control emotion and they do not usually experience regret (Camille et al., 2004). Feeling of regret occurs when an individual compares the outcome of current choice with possible alternatives, but patients with OFC damage are thought to have problems with this counterfactual thinking.

While conducting a gambling task, patients with OFC damage persist in high-risk (low probability of winning) choices to win large money at once and they ultimately lose all the money (Bechara et al., 1994). This impulsive behavior is closely related to the NAcc which is connected to the OFC. The OFC controls the immediate response of the NAcc. If the NAcc is not controlled due to the OFC malfunctions, it is difficult to suppress impulsive behaviors. The suppressive role of the OFC controlling the NAcc can be explained as a general function of the OFC, value representation and value computation. That is, the suppression of impulse is a result of Go/NoGo decision based on comprehensive value assessment. The OFC assesses the values on the expected outcomes of each action and signals them. When the OFC is damaged or underdeveloped, precise calculation of the value of specific action is difficult and an impulsive action is more likely to be chosen.

Another behavioral characteristic deeply associated with OFC damage is the difficulty of reversal learning (Schoenbaum et al., 2007). In reversal learning paradigm, when contingency of stimulus-reinforcement is altered, the new stimulus-reinforcement association is learned only if prior response is changed. However, a monkey with OFC lesion is not able to control responses from prior reinforcement and exhibits perseveration, although it cannot receive further reinforcement (Mishkin, 1964). This is due to the inability to update values of prior actions through negative feedback. Thus, the main function of the OFC is to calculate and update the value of an action through learning new stimulus-reinforcement association.

Unlike laboratory settings, reality poses many issues to consider when making decisions because the outcome is uncertain or risky in many cases. Therefore a precise representation of value judgment is thought to be quite advantageous in suppressing impulsive actions. Recent neuroimaging studies suggest that opportunity for choice is desirable (Leotti et al., 2010) and the anticipation of choice is also rewarding (Leotti and Delgado, 2011). For children or adolescents, however, whose prefrontal regions including the OFC are underdeveloped, the lack of experience limits the representation on values. Therefore, we need to frequently inform them on utility values of learning, provide opportunity to make their own choices, and enhance the quality of value judgment.

REGULATION OF MOTIVATION: GOAL-DIRECTED CONTROL PROCESS

How do people regulate their motivation? The reason people fail to perform tasks persistently and give in to temptation is because immediate rewards are highly favored over delayed rewards. Subjective values of rewards change with the point in time when the rewards are given and immediacy itself plays a relatively important role. If we vary the time and the magnitude of the reward, offer a number of options, and ask the participants to choose one, then they experience a conflict between small but immediate reward and large but delayed reward. One clear point is that as the reward is delayed, the relative value of the reward is decreased. This is called temporal discounting or delay discounting. Temporal discounting is directly related to self-control (Rachlin, 1995) or delay of gratification (Mischel and Gilligan, 1964), and is very similar to resisting temptation or suppressing impulse in its nature. Self-control and delay of gratification refer to the ability to select larger delayed over smaller immediate rewards.

McClure et al. (2004) conducted a study to search the brain areas associated with temporal discounting. They manipulated various monetary reward options at different times (e.g., $20 today vs. $25 after 2 weeks) and compared brain activation patterns during choice. The results showed that the striatum and the MOFC were activated when the immediate reward was selected, whereas the fronto-parietal cortex was activated when the delayed reward was selected. This indicates that selecting the immediate reward activates the reward and value pathway, but to delay immediate gratification, the prefrontal cortex responsible for cognitive control should be involved.

What makes people resist to temptation and control motivation to constantly pursue a specific goal? Controlling impulses

and regulating motivation calls for a detailed planning and execution for future goals. The cognitive control is a central process underlying such regulation, including goal maintenance, planning, performance monitoring, strategy selection, and outcome evaluation. Therefore, the mechanism by which the impulse is controlled should not be understood as a mere suppression of desire, but it should be construed as a goal-directed regulation by a cognitive control.

Cognitive control is actually a very useful coping strategy to modulate motivation to deal with negative RPE or negative feedback. When it happens, the dopamine system becomes less activated decreasing the frequency of target action, ultimately eliminating the learned action. Emotional reactions to negative feedback do no good to control motivation. Rather, one should check for problems of the performance through cognitive control and modify strategies. This may lead to better performance and produce a positive RPE, which in turn stimulates dopamine release to promote motivation and raises the chance of a new learning.

Brain regions associated with cognitive control process are the ACC, the DLPFC, and the OFC (Cole and Schneider, 2007). The ACC which is responsible for executive functions involves in integration of cognition and emotion, attentional control, performance monitoring, error detection, response inhibition, planning of higher-level action, and strategy modification (Holroyd and Coles, 2002). The dorsal part of ACC, which is connected to the DLPFC responsible for working memory, is involved in cognitive functions. On the other hand, the ventral part of ACC is associated with emotional functions (Bush et al., 2000).

Social cognitive neuroscience studies on delay discounting found that individual variability in self-control has been due to the difference in the working memory capacity (e.g., Shamosh et al., 2008). From meta-analysis, Shamosh and Gray (2008) revealed a negative correlation ($r = -0.23$) between delay discounting and intelligence. Other studies also found that activation of the DLPFC has a strong correlation not only with the working memory capacity, executive function, and intelligence but with success rate of various delay of gratification tasks (Knoch and Fehr, 2007; Shamosh et al., 2008). Delay discounting tasks require carrying out cognitive and emotional control simultaneously while calculating the value of selected action. Thus, individuals who are capable of efficiently utilizing working memory have advantages. The DLPFC are recruited during the goal-directed behavior and top-down regulatory processes, including goal maintenance, strategic behavioral planning, and implementation of actions (e.g., Miller and Cohen, 2001; Tanji and Hoshi, 2008). Therefore, self-regulation can be regarded as the process of encoding the value of the goal into VMPFC to make goal-directed decisions and regulating them in the DLPFC (Hare et al., 2009).

A study on brain development in response to negative feedback conducted by Crone et al. (2008) demonstrated that similar activation pattern to that of adults were seen in the OFC for 8–11 age group, and in parietal cortex for 14–15 age group, but no activation was seen in the ACC and the DLPFC up until the age of 14–15. As the DLPFC and the ACC are the regions associated with cognitive control, no activation means that children and early adolescents pose difficulty in reflecting the behavior and searching for alternatives after receiving negative feedbacks. Because this finding suggests that the effort to change the behaviors of children through negative feedback might be ineffective, we need to develop an appropriate feedback system for children and adolescents.

Because self-control is an important cognitive ability that is linked to a wide variety of measures of academic achievement, it would be meaningful to develop self-control ability through training or intervention program. Fortunately, a growing number of studies have shown that working memory training improves cognitive control (Klingberg et al., 2002, 2005) as well as several other cognitive abilities, such as fluid intelligence and problem solving (Jaeggi et al., 2008). This suggests that improving cognitive controllability through working memory training is likely to be far more effective in promoting self-regulation rather than emphasizing the volitional power or boot camp-style training.

AN INTEGRATIVE PERSPECTIVE ON MOTIVATIONAL PROCESSES

By integrating neuroscientific findings on reward, learning, value, decision-making, and cognitive control, I propose a tentative model on motivational processes (see **Figure 4**). In the motivational process model, motivation is defined as a series of dynamic processes including generation, maintenance, and regulation of motivation of which primary functions are approach toward reward, learning through RPE, decision-making based on value, and cognitive control for goal pursuit. These sub processes interact with each other by sending prediction error signals from the striatum to the prefrontal cortex.

First, the motivation generation process is the process in which approach behavior is caused by the anticipation of reward. It is a process of either determining approach/avoidance behavior (Go/NoGo decision) or selecting an action among alternatives, based on the reward value. The reason for a motivation being generated for a previously unmotivated action is because the reward contingent upon a specific action increases the expectation for the reward, which continuously causes approach behavior. The generation of motivation can be judged by the frequency and duration of the approach behavior. The ventral striatum and the amygdala play a significant role in this process. Critical factors for the motivation generation process are incentive salience and reward anticipation from past experiences. And the enemies for this process are the punishment and high level of task difficulty.

Next, learning through positive RPE is a process to continuously maintain motivation. The stimulus-action-reward association is learned to raise the possibility of acquiring the subsequent rewards. When the reward is better than expected, the positive RPE occurs. The larger the error is, the bigger the learner's surprise becomes. And the surprise leads to intense learning (Kamin, 1969; Rescorla and Wagner, 1972). Engraved stimulus-action-reward association enhances the value of a selected action and sustains the target behavior. The negative outcome evaluation, however, wears out positive RPE, which in turn reduces the effect of learning and the value of an action. In the motivation maintenance process, the positive RPE and value judgment are the crucial factors, and experiences of failure and perceived costs are the enemies. The sustaining of motivation can be measured by the frequency
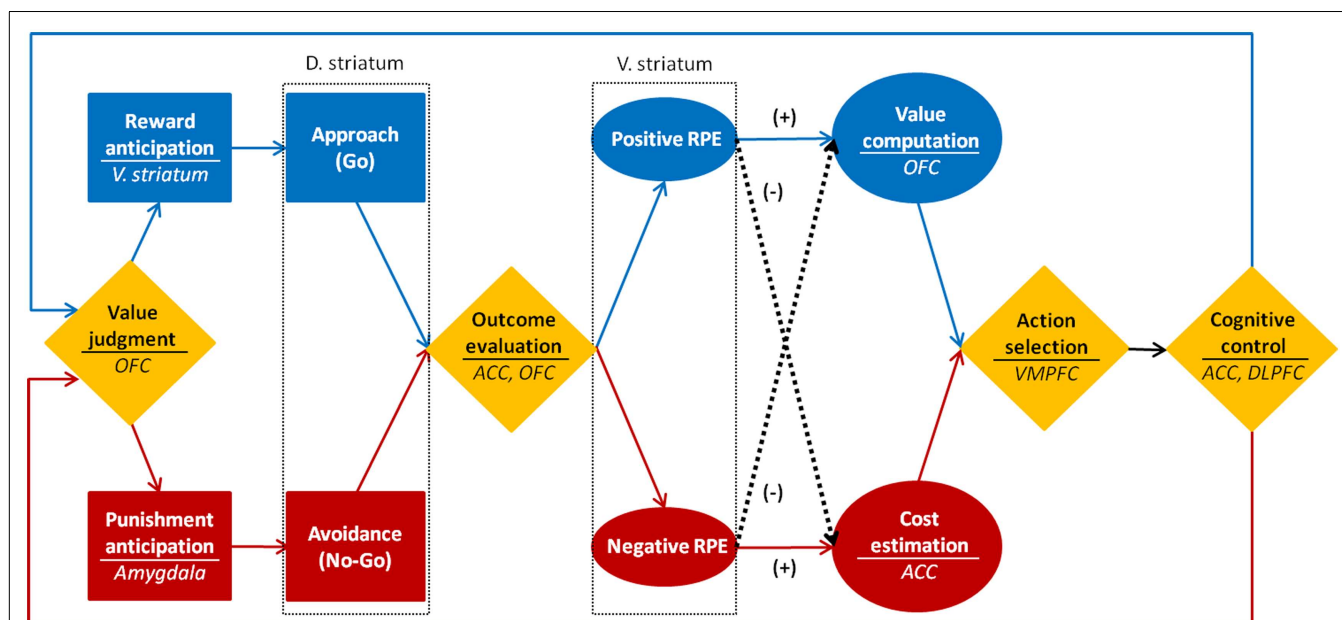
FIGURE 4 | Neuroscientific model of motivational process.

of the action selection, persistence, and efforts. The striatum and the OFC are the main brain regions involved in sustaining motivation.

Lastly, the cognitive control by the negative RPE is a process of self-regulation in fail-to-get-reward situation to pursue goal-directed behaviors and modify plans and strategies to explore new rewards. When the expected reward is not given as a result of an action, the value of the action decreases and the frustration grows bigger leading to diminished approach behaviors, and other alternative actions become massively attractive. This temptation can be resisted by successful cognitive control such as retrieving the long-term goal, monitoring the current performance, establishing a concrete plan, and selecting a new strategy. Motivations can also decline when rewards are always expected because the positive RPE stops increasing. Even in this circumstance, motivation can be promoted through the engagement of the goal-directed cognitive control process of establishing a new goal, plan, and strategy. The enemies for motivation regulation are the immediate impulse, the low executive processing capacity, and the lack of specific goals and plans. Delay of gratification and goal attainment are the barometers for motivation regulation. The ACC and the DLPFC are the main neural circuits related to the motivation regulation process.

A typical example of this motivational process can be easily found in an academic environment. Consider a situation where a student's motivation to learn is generated, sustained, and regulated. A student with no initial motivation to learn a specific school subject may form strong intentions to study the subject for the first time in her life after being complimented or recognized by a teacher (reward-driven approach). Studying harder to get the teacher's praise unexpectedly leads to a better grade (positive RPE). As she already learned, through the association,

what actions to take to keep the good grade, she would put in continuous efforts and be able to maintain the motivation to learn to some extent (value-based decision-making). However, if the grade no longer improves, no more compliments are given by a new teacher (negative RPE), or she gets so used to the compliment that the value of the reward starts to drop (decrease of positive RPE), then she is likely to be in danger of falling for other tempting stimuli. At this moment, by retrieving her long-term goal, she can monitor her current state of performance, modify the plan, and search for alternative strategies (cognitive control). As a result, she can delay the immediate gratification and succeed in motivation regulation.

EDUCATIONAL IMPLICATIONS

The neuroscientific model of motivational processes suggests several educational implications which can be used to enhance motivation to learn. For instance, reward is an essential driving force in the learning environment because approach behavior would not occur without reward. To motivate the unmotivated, the learning process should be rewarding and interesting. Rewards do not have to be tangible ones. Reward in the classroom can be any stimulus which has positive expected values, including positive feedback, praise, interesting activity, utility, relevance, social support, and relatedness. It is important to find out and make a list of appetitive stimuli including a variety of compliments, enjoyable activities, interesting materials, positive feedback, and diverse and novel learning context which can activate the reward circuit of children and adolescents. Since the repetition of the same compliment tends to reduce positive RPE, it is desirable to introduce various reward contingencies in an unexpected way in order to sustain the motivation.

To maintain motivation, the value a specific object and action must be high enough to lead to an action selection. Because the value is learned through trial and error, providing choices in autonomous learning environments would be beneficial for students to form and update their own value. This kind of choice practice may eventually develop the brain regions related to valuation and decision-making. In case the motivation decreases, the roles of attention and working memory cannot be more important. Thus, it would be necessary to develop the training program for these executive functions and to examine its effectiveness. Besides, creating a detailed goal hierarchy between proximal and distal goals and developing specific action plans will help students overcome the failure and temptation. Since the motivational process model proposed in this paper is only a provisional model, more research is required to verify its validity.

Neuroeducation or educational neuroscience is the interdisciplinary research field which builds connection between education and developmental, cognitive, emotional, or social neuroscience. It aims at developing curriculums, learning strategies, teaching methods, learning material, intervention programs to enhance diverse types of learning and ultimately providing optimal learning environments (Ansari et al., 2012; Kim, 2012). Since neuroeducation is a relatively new academic field, the establishment of systematic research paradigm along with intensive research is expected to largely contribute to actual educational settings. With accumulated research findings in the field of neuroeducation, a great deal of progress is being made on the learning and development of cognitive, emotional, and social skills. Nonetheless, research on motivation definitely needs more attention. Neuroeducational research on motivation has advantages for understanding implicit and dynamic aspects of motivational processes because observation and self-report reveal limitations. Choosing a research topic which holds strong ecological validity in educational settings becomes crucial. In particular, more attention should be paid to pragmatic research to enhance students' motivation to learn. For instance, if we can understand the neural mechanisms underlying motivational phenomena such as interest, curiosity, decision-making, addiction, risk-taking, and self-regulation, we can develop a variety of interest-based learning and instruction, curiosity-inducing textbooks, non-threatening tests, and self-control training programs. The neurodevelopmental characteristics of children and adolescents should also be taken into account to optimize the motivation-related brain functions. The neuroeducational approach is also expected to contribute to resolve controversial issues in existing motivation theories and to propose creative theories of motivation beyond traditional conventions.

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Creativity as action: findings from five creative domains

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The present paper outlines an action theory of creativity and substantiates this approach by investigating creative expression in five different domains. We propose an action framework for the analysis of creative acts built on the assumption that creativity is a relational, inter-subjective phenomenon. This framework, drawing extensively from the work of Dewey (1934) on art as experience, is used to derive a coding frame for the analysis of interview material. The article reports findings from the analysis of 60 interviews with recognized French creators in five creative domains: art, design, science, scriptwriting, and music. Results point to complex models of action and inter-action specific for each domain and also to interesting patterns of similarity and differences between domains. These findings highlight the fact that creative action takes place not "inside" individual creators but "in between" actors and their environment. Implications for the field of educational psychology are discussed.

Keywords: creativity, action, art, design, science, scriptwriting, music

INTRODUCTION

Creativity has been studied for more than a century and has recently been a subject of debate in educational psychology (Smith and Smith, 2010). This is because, despite the general consensus that we need more of it, especially in the educational system (Makel, 2009), creativity scholars are still struggling to understand the *nature* of this complex phenomenon and are quite far from designing highly effective programs for *enhancing* creative expression (for a review of education and creativity see Fasko, 2000–2001). Dominant models of creativity associate it with cognitive mechanisms (such as divergent thinking) and personality traits (like openness to experience) but fail, on the whole, to properly engage with the social and material aspects (with a few notable exceptions, e.g., Csikszentmihalyi, 1988). From an educational perspective, this omission is counterproductive as individualistic accounts of creativity place their emphasis on "inner" attributes that are either not fully developed in children or hard to educate (for harmful myths in this regard, see Plucker et al., 2004). Educational systems represent, in the end, a certain kind of environment and, if we are committed to understanding and stimulating children's creative expression, we need a theory of creativity capable of articulating "internal" and "external" facets of creative expression at its different levels: from the most mundane (typical for the school environment) to the highly celebrated and visible.

Under these circumstances, the main purpose of the present article is twofold. At a theoretical level it advances a relatively novel conception of creativity in a landscape dominated by cognitive theories, that of *creativity as action and of creative work as activity*. Conceptualizing creativity with the means offered by the

psychology of action, and in particular by pragmatist approaches to human action, leads to the development of a *situated model* of creative activity. Our second aim is to apply this model to interview data with recognized French creators from five different fields – art, design, science, scriptwriting, and music – leading to a complex image of human creativity both within and across domains of activity. As will be argued in the end, this theoretical approach has significant benefits for the field of educational psychology. A detailed analysis of creative action in the case of established creators can offer important insights regarding what facilitates or constrains creativity and, therefore, enable us to think about effective and domain-specific ways of stimulating creative expression in both children and adults.

CREATIVITY IN AND AS ACTION

An inquiry into how creativity "takes place" is necessarily one that concerns itself with models of the creative process. Traditionally this process has been considered to be *mental/cognitive* in nature and *individual* in manifestation (see Glaveanu, 2010). Furthermore, the first models to be proposed excelled in depicting a rather orderly and simplified succession of stages for it, usually four. Wallas (1926) offers a classic example in this regard with his well-known distinction between preparation, incubation, illumination, and verification. Subsequent models added both complexity and dynamism to these initial proposals. Mumford et al. (1991), for instance, described a more elaborate succession of stages – problem construction, information encoding, category search, specification of best-fitting categories, combination and reorganization of best-fitting categories, idea evaluation, implementation, monitoring – and indicated many feedback loops

among them. Botella et al. (2011) proposed a dynamic approach to the artistic creative process in which it is possible to "jump" some stages, to realize some simultaneously, and to go back to previous work phases. As Lubart et al. (2003) noted, early concerns with the creative process resulted primarily in stage models and generated sustained arguments about the exact number and characteristics of each stage. In contrast, more recent theories shifted the focus to *sub-processes* and the *micro-level dynamic* of creativity, conserving nevertheless a predominantly cognitive perspective on the phenomenon (e.g., Ward et al., 1999).

In contrast to purely cognitive models, action theories of creativity start from a different epistemological premise, that of *interaction and interdependence.* Human action comprises and articulates both an "internal" and "external" dynamic and, within its psychological expression, it integrates cognitive, emotional, volitional, and motivational aspects. Creativity, from this standpoint, is *in action* as part and parcel of every act we perform (see Joas, 1996). Creativity exists on the other hand also *as action* whenever the attribute of being creative actually comes to define the form of expression (and, as such, we can talk of "creative work" as different from other types of work which, in themselves, don't completely lack the attribute of creativity). This particular understanding of creativity is not on the whole absent from past and present literature (see Glaveanu, 2012a). Woodman and Schoenfeldt (1990), for example, advocated some time ago for an interactionist model of creative behavior, one that starts from an understanding of the "organism-in-its-environment". A strong link between creator and situation also characterizes Gruber's evolving systems approach to creativity (see Gruber and Wallace, 1999) and its emphasis on ecological, longitudinal, contextual, and situated investigations. The creator is an evolving system within larger evolving systems (professional, social, political, etc.) and his or her action is always contingent on this dynamic co-evolution (see also Csikszentmihalyi, 1988).

But, in the end, what is action? The notions of act, action and activity have been theorized since the beginning of the past century by thinkers from a multitude of different schools of thought, spanning from American pragmatism to Russian cultural-historical psychology. Relatively dormant under the prominence of behaviorism and then cognitivism, they re-emerged in the past decades especially as part of social and socio-cultural psychology. In cultural psychology, the concept of activity is essential for understanding the development and manifestation of the human psychic in various cultural contexts (see Eckensberger, 1995; Cole, 1996; Ratner, 1996; Wertsch, 1998). Human action is defined by its intentionality and the mediation of various systems of tools, signs, and artifacts that make it comprehensible and symbolic. It takes place in a setting and involves both the organism, in its unity between body and mind, and a socioculturally constructed environment. Finally, action is often joint action and is both facilitated by and facilitates human social relations. These characteristics of action are present in John Dewey's work, the leading pragmatist who, beside his writings on education, democracy, nature, and esthetics, was also an important theorist of activity (see Miettinen, 2006). From his rich intellectual legacy, we will be focusing here on one of his most celebrated works, "Art as experience," first published in 1934, in order to reconstruct his vision of human action.

For Dewey, what brings action and creativity together is *human experience*, defined precisely by the interaction between person and environment and intrinsically related to human activity in and with the world. A graphic representation of his conception is offered in **Figure 1** below (see also Glaveanu, 2012b). Action starts, as depicted, with an impulsion and is directed toward fulfillment. In order for action to constitute experience though, obstacles or constraints are needed. Faced with these challenges, the person experiences emotion and gains awareness (of self, of the aim, and path of action). Most importantly, action is structured as a continuous cycle of "doing" (actions directed at the environment) and

FIGURE 1 | A model of human experience (after Dewey, 1934).
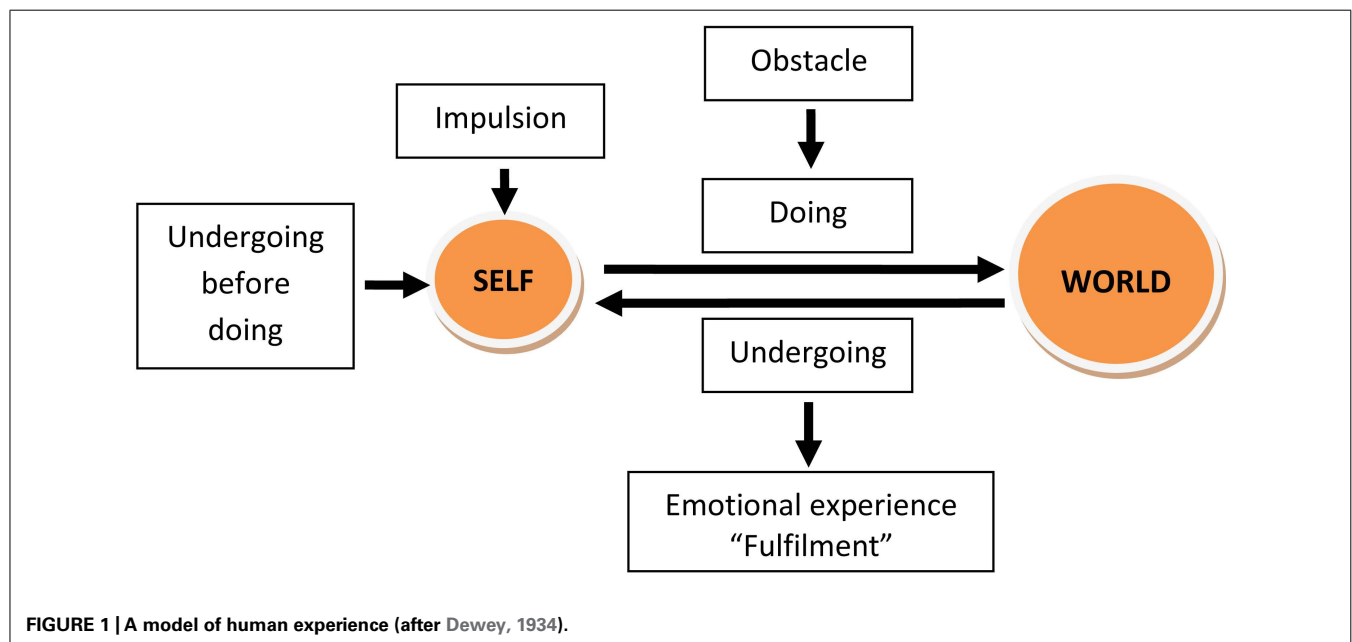
"undergoing" (taking in the reaction of the environment). Undergoing always precedes doing and, at the same time, is continued by it. It is through these interconnected processes that action can be taken forward and become a "full" experience.

The framework presented here is relevant for our understanding of creative action and Dewey himself has elaborated it in relation to art and the activity of the artist. The creator acts on the world in an attempt to materialize an artistic vision. However, this action is pared by a reaction from the world, one that the creator needs to undergo, to be aware of and integrate, in order to continue the work. In Dewey's words (1934, p. 116), art:

"is a developing process. (...) the artist finds where he is going because of what he has previously done; that is, the original excitation and stir of some contact with the world undergo successive transformation. The state of the matter he has arrived at sets up demands to be fulfilled and it institutes a framework that limits further operations."

As such, for Dewey, artistic work is not the outcome of the artist alone, and neither of the work of art. Creative expression is precisely "located" at the interaction between self and art object (Benson, 1993). Such a description resonates widely with many conceptualisations of artistic work (see Getzels and Csikszentmihalyi, 1976, discussion of the role of tension in art) and also with the experience of artists themselves. Israeli (1962) for example, in proceeding with a series of self-observations while painting, noted that "check and evaluation of the operations and outcomes are followed quite often by plans, suggestions, and decisions which control the subsequent operations on the painting" (p. 256). The continuous *cycle between doing and undergoing* that is at the core of Dewey's conception seems to express a valid approach in the case of art, and, potentially, beyond it. It is argued here that the framework depicted in **Figure 1** has indeed a broader applicability in the psychology of creativity and constitutes, among other things:

- A model of the creative process based on cycles of doing and undergoing;
- An integration of behavioral, cognitive, emotional, and motivational elements;
- A re-evaluation of "impulsion" and "obstacle" as defining features of creative work;
- A contextual and relational account of human creativity.

THE PRESENT STUDY

The study presented here focuses on creative activity within five creative domains: art, design, science, scriptwriting, and music composition. By applying the action framework proposed above, we explore the generalities and specificities of the doing-undergoing cycle in *each* domain and *across* domains. This framework can be potentially applied at three levels of analysis: a micro-level, focused on creative acts as they take place; a mezzo-level, concerned with the creation of a particular work or series of works; and a macro-level where the unit is the larger scale of creative activity, oftentimes the lifetime work of a creator. Considering the fact that we will rely on interview data, there is a possibility of uncovering elements belonging to all three levels but essentially, in lack of micro-level observations, the conclusions will be formulated at mezzo and macro levels. As such, the research is *exploratory* in nature and guided by the following general questions: What are the impulsions? What kind of obstacles do creators come across? What do they do? What do they undergo? How does the cycle of doing and undergoing actually take place? What are the main sources of "undergoing": social, material, personal, etc.? Is there fulfillment and how does it contribute to the creation of full experiences? This investigation allows us to build more particular descriptive "models" for each of the five domains in terms of all the elements above and, by using the same scoring grid, to compare the creative action of artists, designers, scientists, scriptwriters, and composers.

MATERIALS AND METHODS

PARTICIPANTS

The sample consisted of 60 professional creators, 12 from each of the five domains, currently living and working in France. The main criterion for selection was for respondents to have extensive experience in their domain (overall, on average, the work experience ranged between 10 and 20 years). Demographic characteristics of the sample are presented in **Table 1**. As can be noticed, over two thirds of the participants are male, the distribution between sexes varying according to domain. Age also varies, the average for all domains except music being between 40 and 50 years.

All respondents had received higher education, in most cases directly specializing in their current profession. Important to note, the five groups are not completely homogenous in terms of creative output. Artists in the sample were primarily sculptors and/or painters, a few working with video and photography. Designers covered a more varied type of production, from decorative objects, interior design and furniture to visual communication, logos and packaging. The scientists group included six physicists (and astrophysicists), three mathematicians (theoretical and applied mathematics), two information and technology specialists and one chemist. Scriptwriters were more uniform, all writing film scripts for cinema or television. Finally, the musicians were composers working on either instrumental or electro-acoustic pieces.

MATERIAL

The method used for data collection was represented by *semi-structured interviews* following a similar topic guide across domains. The interview started with a general presentation of the participant, continued with a description of his/her work and activity and, in the last part, invited a reflection on the creative process and the place of the creator and his/her domain

Table 1 | Demographic characteristics of the sample.

	Art	**Design**	**Science**	**Scriptwriting**	**Music**
Sex	7 m 5 f	8 m 4f	11 m 1f	6 m 6 f	10 m 2f
Mean age*	47	41	42	49	53
Age range*	35–66	24–60	28–57	40–63	36–63

There were a few missing values for age: 3 for design, 4 for science, and 5 for music.

in society. In particular, an adaptation of the critical incident technique (see Flanagan, 1954) was used in order to elicit more precise descriptions of respondent's creative work. Interviews usually lasted between one and 2 h and were afterward transcribed verbatim for the purpose of analysis.

PROCEDURE

The participants were approached and fully informed about the project before the interview took place. Their consent was registered and anonymity guaranteed. After the interview, all transcripts were subjected to thematic analysis (see Attride-Stirling, 2001) and the coding frame was *both theory and data driven*. The main analytical categories were offered by the framework presented in **Figure 1** (impulsion, obstacle, doing, undergoing, emotion) but their subcategories were defined after a preliminary coding of the first interviews from each group. As such, in the end, the coding frame included 11 codes, a summary of which can be found in **Table 2**. A similar coding frame had been elaborated and used successfully in previous research concerning creativity in craft activities (Glaveanu, 2012a,b).

After finalizing the coding frame, a second coder, familiarized with the theoretical framework, applied them to all 12 interviews of the art group. On average there was 93% agreement between coders, with some discrepancies mostly for "undergoing – social" and "undergoing final result." This led to refining the initial definitions and then to the application of the updated coding frame for the entire sample with the help of the qualitative analysis software

Atlas.ti. Following this stage, all relevant quotations for each code were retrieved, separately for each domain, and summarized thematically by considering their content. For example, in the five domains, the "doing – stages" code included a series of different actions (such as documentation, sketches, creating the final product, etc.). Establishing the exact work phases in art compared to music composition, as well as their "order," was done by reading all the material coded under "doing – stages" and retaining only convergent information (i.e., what most creators in the particular domain had in common). This allowed us to build general schemas of creative action for each domain, synthesizing findings from the main codes: impulsion, obstacle, doing, undergoing, (before doing, material, and social) and emotion. The schemas are presented and explained in more detail in the results section. Whenever direct or indirect quotations are used, they are indicated as such by mentioning the respondent code (A – artists, D – designers, S – scientists, L – scriptwriters and M – musicians; order numbers range from 1 to 12).

RESULTS

CREATIVE ACTION IN ART

As depicted in **Figure 2**, the creative activity of artists generally starts from the *impulsion* to create or make, to "do" or "incarnate" (A3), and it is also fed by a curiosity to see and understand (A6), to "find sensations" (A5), and a need to express (a "narrative desire," A1). Artists refer often to their work as a "physical" necessity (A7) and to its motivation as a form of "internal pressure" (A9). This

Table 2 | Coding frame.

Code	Definition	Examples
Impulsion	The motivation for action: why the person is doing a certain action	The need to create, to learn new things, to write, to express, to know (curiosity), to touch, etc.
Obstacle	Difficulties and/or limitations on the whole or at different stages	Lack of money, lack of time, lack of support, "inspiration block," etc.
Doing – stages	The different stages or phases of creative work and how it advances	Documentation, first draft, maquette, prototype, final outcome, etc.
Doing – procedures	The different techniques creators use at different stages of their activity	Taking notes, using forms of brainstorming, using repetition, deformation, making associations, etc.
Doing – tools	The material tools used	Paper, pencil, brush, colors, wood, computer (different types of software), metal, glass, etc.
Doing – Time/place	When and where creative work is done	In the "atelier," at home, at university, in the morning, evening, at all times, etc.
Undergoing – material	The relation to the physical/material environment	Constraints and properties of materials or the technology involved
Undergoing – social	The relation to the social environment and the nature of social interactions	With clients, colleagues, family, collaborators, critiques, audience; issues of social recognition
Undergoing before doing	Everything that prepared the creator for the work	Reading, discussing with others, preparing the instruments, studying, seeing exhibits, etc.
Undergoing final result	Perceiving and judging the final outcome	Looking at what came out, judging when and if it is finished, its quality, etc.
Emotion	Emotional experience at the beginning, during and at the end of activity	Sadness, happiness, excitement, satisfaction, depression, anxiety, joy, dissatisfaction, etc.

FIGURE 2 | Schematic representation of creative activity in the case of artists.
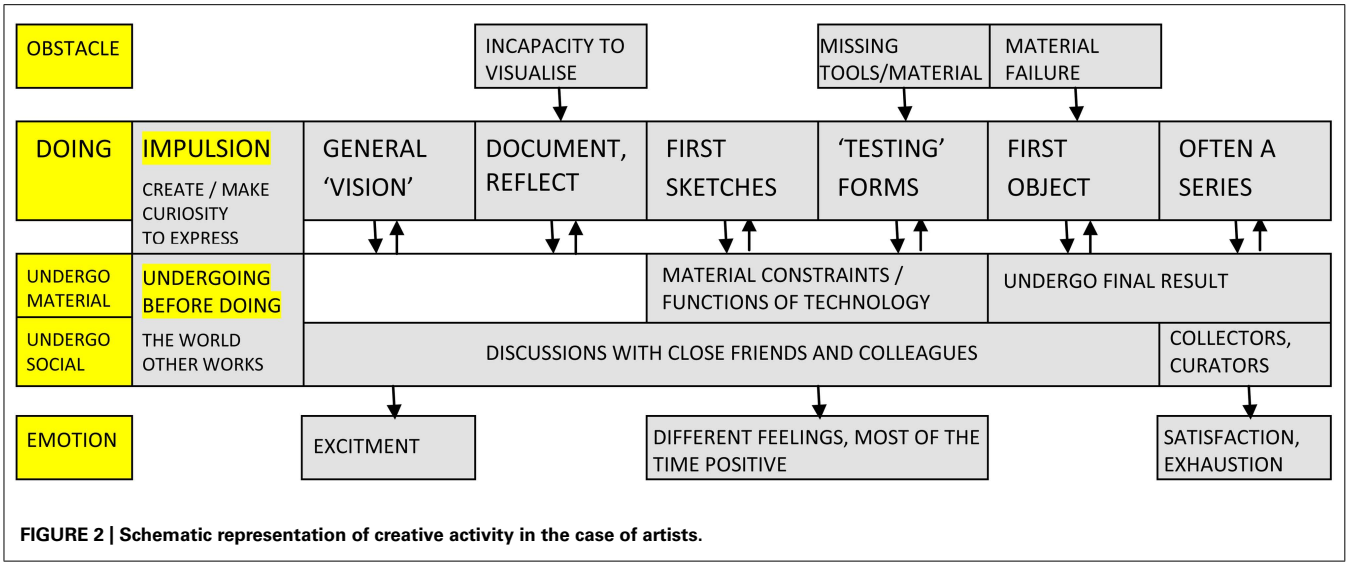
intense motivational drive meets certain *obstacles* when it becomes manifest, mainly the incapacity to visualize (A2) and reach a creative idea, missing the tools to work with (A5) and, toward the end, at times, the failure of material support (A10). Artistic activity seems to be defined, for most respondents, by a series of "crises" (A3), a constant self doubt and a desire to start everything afresh.

In terms of the *time and place* of their activity, most artists are very irregular, they don't have specific working hours, mix activities and often get to work in different places. They take pride in not having "office work" (A5) although the most frequent place, at least for fabrication, is their studio. Several work at night, more as a matter of "germination" than urgency (A1). As for the general stages of their "*doing,*" the most frequent succession of stages is included in **Figure 1**. The whole process starts normally with a "vision" or idea. The "click" comes usually after a period of void, of wandering (A7), and the exact trigger can take many forms (for example an image, A9). This initial idea is nevertheless schematic, necessarily incomplete, and needs a time of reflection, documentation, incubation. These initial stages of "conception" lead to the stages of "fabrication" (A9), starting with the first sketches (e.g., the maquette) and up to a "draft" and the final object. Ideas are typically tested and experimented with on the basis of drawings and material depictions of the work, in clay or cardboard. The end result is often a series, as the first piece does not "exhaust" the sought after sensation (A6). Within these formal stages, there are numerous work *procedures* artists employ to realize their vision, including repetition (A8), multiplication (A10), permutation of elements and inversion (A2), simplification (A1), and change of medium (A9). Most of the time, the process is based on repetitive gestures, which for some are a means of relinquishing intentionality and "subjective decision" (A2, A4). Finally, the *material* medium involved is very diverse, including paper, pencil, computers, clay, metal, watercolors, acrylic, brushes, wood, plaster, latex, burin, ink, etc.

Before engaging with work, artists *undergo* family influences (A11, A12), and also formal, university training. The latter is

considered by some not truly formative (A6), because most of the time inspiration comes from the world and the works of others. In the words of one respondent, "the first stage is life" (A1). The artists often consider themselves "sponges," "90% of the time in a receptive state" (A4), allowing themselves to be "impregnated" by things and people (A11) who thus enter an inner "factory of fermentation" (A4). The walks, voyages, readings they make and exhibitions they see all nourish creative impulses. This is exacerbated by the "tactile" nature they seem to possess, where "observation goes through the hand" (A3). The *material undergoing* is marked by this "physical, sensorial, sensible presence" of the work, the "confrontation" with it (A6). Artists are always aware of and recognize material constraints, for example the chemical properties of pigments (A1). Objects "guide" the work (A10), they "speak" to the creator (A2), "call" each other (A8). In particular, objects resist the intentions of the artist. All of the sudden, they "ask a question" (A3) and very often "change the original plan," being "stronger" than the creator, "imposing their rules" (A10). This is exactly what artists love about their work, this resistance, this reaction, this dialogue: the fact that the material all of the sudden says "wait, it is not just you!" (A12). Accidents enrich the project and one needs to constantly be on the alert for them (A5). But ideas also come from collaborators and the area of *social undergoing* is well represented. At times, the starting point of a project is an encounter (A4) and the entire process of work is collaborative. When this is the case, the partner is considered a "third eye" (A8) and the moments of discussion, even arguments, become a necessity (A1, A3). One needs "to see how others look at the work, to be able to see it as well" (A5). And "others" are also spectators and audiences. Social recognition gives pleasure and, whereas some confess showing "extreme permeability" (A4), others strongly affirm that their works is not meant to "seduce" (A7).

This multifaceted process of creation is unsurprisingly associated with different *emotional* states. The excitement of the creative idea is usually followed by a variety of emotions, while working. These range from pleasure and satisfaction to melancholia and even desperation but, most of the time, the reported states are

positive and have to do with the "jubilation of being alive" (A6), the "pleasure of making" (A4) and above all the inner "certitude" (A9) when you are about to "do something" (A12), when the work starts "making itself" (A7). Confronted with the stereotype of the creator in turmoil, artists in this group were ready to contradict the myth and claim that they work to be happy and when happy (A10, A11, A12). The end of the creative process and *undergoing of the final result* are for all a delicate time when satisfaction mixes with exhaustion (A11) and the product is judged in terms of the initial vision and reaction of the audience. In a sense, some agree that an artistic object is "never finished" (A1), and take comfort in the perspective of having the work "back" and working it further (A9). This testifies to the continuity and cyclical nature of artistic activity, making the schema presented in **Figure 1** only a portion of a process filled with feedback loops, for working and reworking the work of art.

This *dynamic between doing and undergoing* is fully captured by artists who, in their interviews, often refer to their work as a series of "back and forth," "come and go" (A2) between an initial imperfect and incomplete idea (A1) and external conditions that help the plan "mature" and keep it "flexible" (A4). Cycles of "action, reflection, action, non-action, plenty of action" (A7) describe the creation of art, during which the artist controls the process and at the same time lets it control the outcome (A8). This shapes the *experience* of art as something at the same time "rewarding and ungrateful" (A1) but, above all, defined as a "space of jubilation" (A2), of "extraordinary freedom" (A3) and of "pure magic" (A5).

CREATIVE ACTION IN DESIGN

Designers share some important similarities with artists, but also some clear differences, as can be observed from **Figure 3**. To start, the work of designers has its roots in similar *impulsions* to "make" things, to "build" (D3, D7), and also to "touch," to work with one's hands (D3, D8). The need to create and to be original and generate a "surprise" was also noted by some (D5, D3, D4), as well as the need to transform, change, and experiment (D2, D9). Specific to designers, they are also motivated by a desire to solve a practical

problem (D3), and through this to respond to a certain need (D3), coming from a client. This presence, pressure and guidance offered by the client's brief are almost universally mentioned. *Obstacles* reflect this to some extent and many discuss the financial and time constraints put on their activity (D3, D7, D11, D12), as well as "technical" difficulties (missing the proper technology; D6, D8, D11, D12) and being at times "blocked," missing inspiration (D7, D8, D9, D10). Conflicts with clients are also mentioned as a source of stress (D7) as well as some self-imposed constraints (not to be too "literal," D6; to strive toward simplicity, D7, etc.).

Similar to artists, most designers do not work every day according to a schedule and feel the need for some variation of their daily routine (D5). However, in their case, "availability" and external demands organize the work process and those who have a fixed studio work primarily from there (D3). Designers distinguish clearly between working for a client and working for oneself, in which the former is much more constrained and comes with some pre-set guidelines. The *stages of doing* can nevertheless be distinguished in both cases as starting from a general idea and gradually working toward its "concretisation" (D7). Just as in the case of artists, work starts from an idea (D4), an "intuition," the "embryo" of the final form (D5). Certainly, whenever there is a client brief, the starting idea can be better defined, although this is not necessarily the case. The documentation stage is important, and, when time allows, quite extensive (D8 compares it to "going shopping" for elements). First externalizations of ideas take the form of drawings and sketches, and are progressively followed by 3D computer modeling (D4) and/or physical mock-up (D3, D9). On the basis of these steps, the form is perfected and several of its details are progressively defined (D10). The prototype stage can be optional (D2) but at times it is required, especially when there is scope for "industrialization" (D12). It is usually the case that designers present several ideas to the client (D7, D8, D12) and therefore several prototypes are made. The final object can require collaboration with technicians (D5) and an official presentation to the client (D11). The repertoire of work *procedures* involved in the stages above is extensive: amplification, deformation (D4, D12),

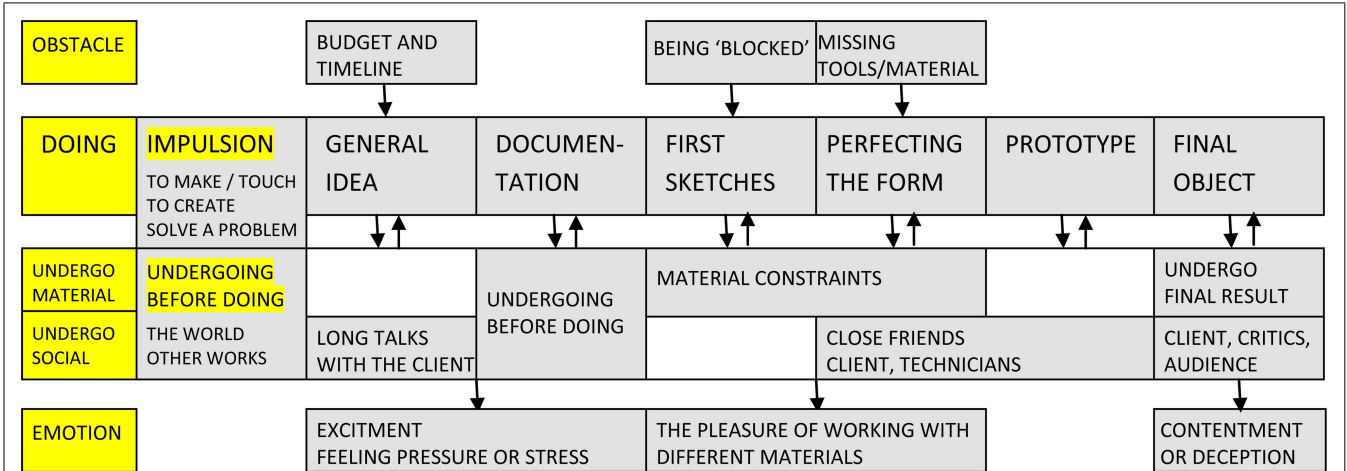| OBSTACLE		BUDGET AND TIMELINE		BEING 'BLOCKED'	MISSING TOOLS/MATERIAL		
DOING	**IMPULSION** TO MAKE / TOUCH TO CREATE SOLVE A PROBLEM	GENERAL IDEA	DOCUMEN- TATION	FIRST SKETCHES	PERFECTING THE FORM	PROTOTYPE	FINAL OBJECT
UNDERGO MATERIAL	**UNDERGOING BEFORE DOING**		UNDERGOING BEFORE DOING	MATERIAL CONSTRAINTS			UNDERGO FINAL RESULT
UNDERGO SOCIAL	THE WORLD OTHER WORKS	LONG TALKS WITH THE CLIENT			CLOSE FRIENDS CLIENT, TECHNICIANS		CLIENT, CRITICS, AUDIENCE
EMOTION		EXCITMENT FEELING PRESSURE OR STRESS		THE PLEASURE OF WORKING WITH DIFFERENT MATERIALS			CONTENTMENT OR DECEPTION

FIGURE 3 | Schematic representation of creative activity in the case of designers.

association of ideas (D2, D8), use of allegories (D6), schematisation, and simplification (D7, D8, D11, D12), the re-use of shapes (D4), synthetic thinking (D9) and plenty of calculations (D11). Designers tend to have a notebook with them at all times, because ideas can come even in the middle of the night (D5). The range of *materials* used is also impressive, and includes, among others: paper, wood, cardboard, clay, metal, glass, textiles and cotton, steel, foam, leather, and plastic.

This attraction toward materiality was present for many since early childhood, when they engaged constantly in making or creating things (D7, D8, D9, D11, D12). As in the case of artists, the main sources of *undergoing before doing* are represented by the world and by other works. "Inspiration comes from everywhere" says D1, and the "starting point" is found while walking on the street, reading, taking the metro (D5). The important thing is to always "keep the antennas out" (D10), to be "attentive" and "open to the world" (D5), to "collect things" (D11) and "store them" in a "bank" of ideas (D9). "Creation is ultimately the reuse of a body of things that have been seen, read, digested, and it is the ability to re-fit, or to deliver, give life to this memory" (D2). Going to museums and exhibitions is a vital part of this process (D7, D10, D11) as one is "nurtured" by the work of others (D6). A special relation is set in place between the designer and the world of objects: "the designer is in the concrete" (D12). Forms of *material undergoing* are often mentioned in the interviews, from the need to explore materials, to "test their limits" (D3), to the frustrations one experiences when not "feeling" the fabric (D8). Material properties are to be discovered, to learn and re-learn with each new encounter. The maquette stage is particularly important for this, to "see what happens," how materials "react" (D4). Only through these trials can the designer get to acquire "the intelligence of the materials," to remember their solidity, rigidity, flexibility, or fragility, and to know exactly what needs to be used and when (D11). A designer's creative activity is a game of constraints (D3, D4, D8), of "happy" accidents (D7), and moments of distancing and reflection (D9, D10). Distance is also achieved through the look of others, close friends, and collaborators (D3, D6, D9). However, when it comes to *social forms*

of undergoing, it is the figure of the client that dominates. On the whole, designers seem to have an ambivalent relation with clients. Whereas some acknowledge the power of clients to decide how the work is done and when it is finished (D7, D8), others comment on the freedom of the designer, as constrained as it may be, to decide on the final form (D1) and propose alternatives (D4). Ultimately, there is a constant interaction with the client, back and forth exchanges (D1, D8), especially at the beginning and toward the end. Also, designers interact with technicians and engineers (D12) and with consumers (D6). In this context, some comment on the general lack of recognition for designers in society (D7).

Creative work is accompanied by different *emotions*. The beginning of work is exciting (D6) but can often generate stress and anxiety (D10) due to external pressure (D7). Usually the work itself is enjoyable (D6), marked by the pleasure of creating, of "making" (D9, D11). However, there can also be an anxiety for missed possibilities (D7) and a persistent doubt about the direction of the work (D10). The end brings satisfaction (D2), especially when the client is pleased (D10). An "artist" is never truly satisfied though (D1, D7) and the final product can generate "great surprise but also great deceptions" (D12). In general, the outcome is judged based on its esthetics (D11) and capacity to address the problem (D12). Its value is "relational" and so is its origin: "In the end, the project is a mixture of the original idea and then of the chances we came across, the meetings, so to speak, positive or negative, with materials, with techniques" (D5). The idea of the *dynamic between doing and undergoing* clearly emerges in this quote, and in all references to work as "trial and error" (D2), as going "little by little" (D3) in an almost "experimental process" (D4). The concept is there from the start but it is not complete, it changes (D1) and doesn't yet have a form (D2). It is all finally "a permanent dialogue between myself and the object" (D10) that defines the very *experience* of design.

CREATIVE ACTION IN SCIENCE

Figure 4 depicts the activity schema in the case of scientists. There are notable differences from artists and designers. To begin, the

FIGURE 4 | Schematic representation of creative activity in the case of scientists.
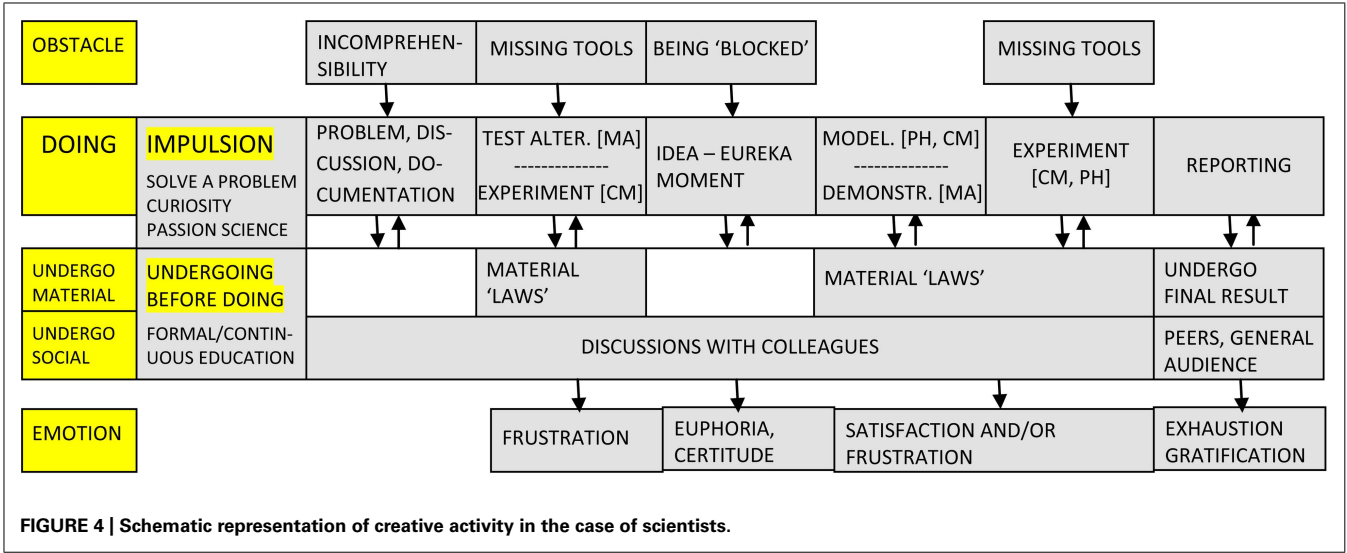
impulsion that drives scientists toward their work mainly concerns the need to "solve," to find an answer to a problem or question (S1, S2) and learn something new (S1, S4), coupled with great curiosity (S2, S5, S8). Many scientists mention also their passion for the domain of their choice and the pleasure they derive from working within it (S4, S6, S12, S7, S8), their need to go further in their domain (S7, S8), to arrive at new and different results (S5). A first *obstacle* for them is incomprehension or the inability to solve and understand (S2, S5), often associated with a feeling of being "blocked". Missing proper tools is another major concern for scientists who depend on technology (S3, S5, S9, S10) and the mathematical apparatus (S7) to perform their research. All these difficulties can be traced back to the complexity of the phenomenon under study (S7) and for some, like astrophysicists, the impossibility of having direct access to certain physical realities, for example planets and stars.

The *time and place* for scientific activity tends not be fixed (S12) and some days are more productive than others (S1). However, unlike artists and designers, scientists are more committed to a stable working place, their university and their office, which is compared to a protective "cocoon" (S6). On the other hand, most refer to the continuous process of thinking as one can reflect on a problem from morning until late (S5). The actual *stages of doing* vary according to discipline but, overall, "there is the obsessive period, there is the enlightened period, and a period when you sweat hard to put things into shape" (S4). In more detail, and somewhat independent of the specific discipline, scientists start with a stage of discussion and documentation when the problem arises. Problems can come from anywhere, from articles, discussions with colleagues or attending seminars (S2) and their emergence is followed by substantial work in the library (S6). What is vital at this stage is for the "good questions" to be posed, because "in research, it is more important to find the questions than the answers" (S9). Then the work process becomes differentiated. In mathematics there is a long period of eliminating "false tracks" and, once the right idea "comes," a demonstration for it needs to be set in place (S3, S4). In chemistry, experimental results prompt further questions and ideas, these are then modeled and again tested experimentally (S5). In theoretical physics and astrophysics, scientists collect observations, build a model and then test its assumptions (S1, S7). Finally, IT specialists in our group deal with creating computer systems and employ an experimental approach (S12). For all the scientists, however, a special stage is the idea or Eureka moment, usually "instantaneous" (S3), coming when least expected (S4). In contrast, the last phase of reporting, characteristic again for all, can be boring, tedious and non-creative (S1), "less amusing" (S4), although necessary (S7).

In terms of the *procedures* used, by and large scientists have two broad options in their work: to develop a new technique or use what already exists (S1). As for the second option, this can be done either by applying existing theories and models to recently discovered phenomena (S3, S5, S9) or by modifying or adapting procedures to fit the problem at hand (S3). More specifically, scientists strive toward parsimony (S7, S8), breaking down more complicated problems into simple ones (S10) and work by making connections between problems and domains (S6). Finally, when it comes to *materials*, the range seems more limited than

that of artists and designers, being constituted primarily of books and articles (S2, S4), paper and pencil (S3, S4, S5). Computers and the Internet are "indispensible," "omnipresent," a real "right hand" (S1). To this we need to add experimental machines and technologies (S5) and lab equipment (S8).

As a precondition in science, all respondents experienced long years of formal education, of "apprenticeships" (S1) that helped them build their "general scientific culture" (S2). The *undergoing before doing* is completed by a more informal and continuous process of learning beyond one's academic training. Reading books and articles, going to seminars and conferences (S2, S5, S6, S7) is fundamental. In all the fields above "you are always forced to learn something" (S4) and get to monitor and "devour" technical progress (S11). As previously mentioned, there is "enormous library work" before a study (S6) because you do not want to get to demonstrate what has already been demonstrated (S3). Discussions with colleagues supplement this effort and help ideas emerge or take shape (S7). At times, certain concerns and questions are "in the air" within the scientific community, and scientists pick them up and work on them (S1). This relates also to the notion of *social undergoing*.

Contrary to the popular image of the lone genius, if there is anything that defines scientific work it is the fact that it always happens with others, alongside others, in relation to others (S10). First points of contact are colleagues and peers, who play a crucial role in proposing problems (S4), formulating ideas (S6, S8, S9), clarifying them (S12), orienting the work (S2, S10) and finally evaluating it (S1). "There is a collective dimension and teamwork in the process of creation" (S5) and often it is the case that two or more people work together and have an ongoing critical exchange (S11, S12). In such circumstances, it becomes impossible in the end to know who had which idea (S7). Work "advances through meetings" (S4) and, at a broader level, scientific careers are shaped by the entourage and the chance of working with certain people (S5). The larger scientific community is a reality taken into account by all because scientific outcomes are there to be scrutinized and judged (S5, S8). There is a need for recognition (S6, S8) and, in an effort to gain status (S5), a scientist has sometimes to do a bit of "marketing" in promoting his/her work (S1). After all, there is "fierce competition" (S7, S8) in science, perhaps even more than in other creative domains. Another major source of undergoing comes from the *material world* and again the scientist's activity is never as far from it as imagined. In physics, for example, there are laws, absolute laws, and "the phenomenon imposes incredible constraints," "observable quantities" that defy all "creative calculations" (S1). Physics in this respect "guides the physicist," and defines a precise space of possibilities (S7). Chemistry is not far from this because here as well a "game with matter" takes place (S5), and this matter resists and responds. As such, there is in science room for accidents and surprises, for unpredictable results (S9) and theories that need to adapt to the evidence of "experience" (S8).
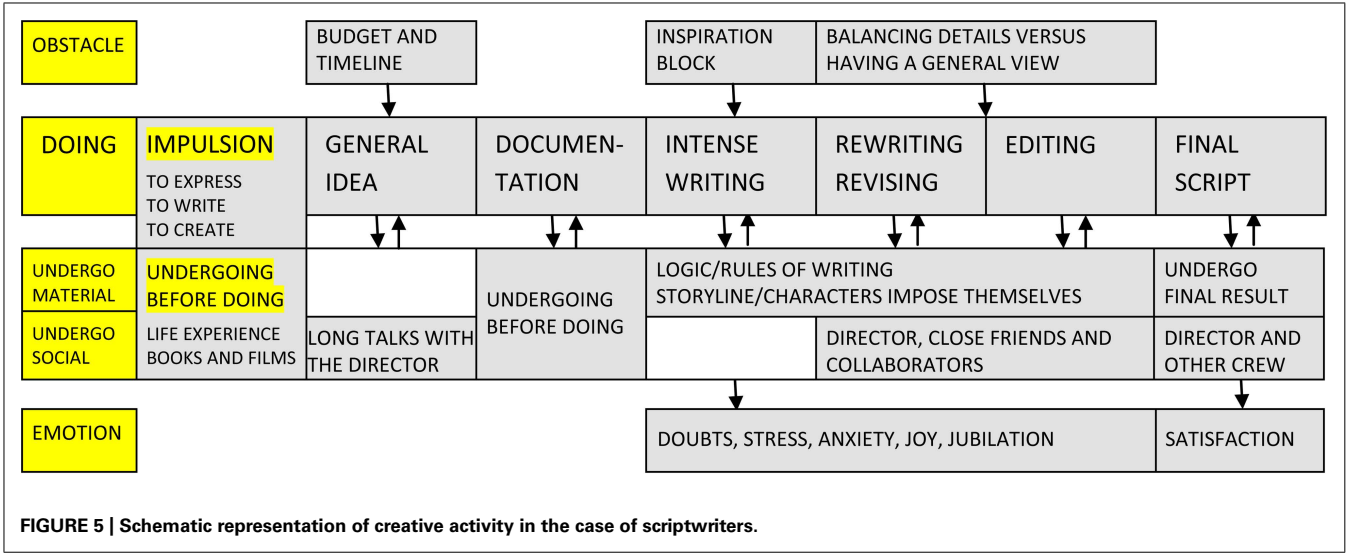
And surprises also generate diverse *emotions*, depending on the stage and domain. Before getting the idea, a feeling of frustration often accompanies the search (S5, S8) and the Eureka moment is always associated with "excitation" (S4, S5, S7), an enormous satisfaction (S1, S10) close to euphoria (S3). This moment of

certainty and inner clarity leads to a long period of testing and formulating that can be gratifying, when calculations go well (S1), but can also be associated with "suffering" during report writing (S4, S7). When work is finished, there is satisfaction and pride (S5) but also depression (S4) and anxiety about presenting it (S7). Overall, the ups and downs of scientific activity remind some of a manic-depressive state (S10), in which exaltation lives side by side with total exhaustion. This mirrors closely the general *dynamic of doing and undergoing* specific for scientific efforts, one in which "we advance, we are blocked, we reflect for a moment, we advance some more" (S2). A constant cycle of observation, modeling and testing (S7) takes place in science and shapes the *experience* of it, in which excitement and suffering are integral parts (S4).

CREATIVE ACTION IN SCRIPTWRITING

The activity of scriptwriters, depicted in **Figure 5** resembles, to a certain extent, that of artists and designers. Fundamental for the *impulsion* of writers is their need to express (L2), to "tell" or "speak" (L5, L6), to show the world (L5) and "stage" something (L9). This is associated with a particular desire to write, a desire so strong that it makes some conclude: "if I wouldn't write movies, I would write novels" (L6). Another important need is to create, to make something new and "provoke" others (L2). The act of writing or creating is never void of motivation because almost all respondents commented on the fact that they work with "ideas that evoke a desire" (L5), that "tell me something," address the writer him/herself (L8) and this desire is to be clarified from the start. Finally, some have a more social motivational basis as well and feel the need to collaborate with certain producers or directors (L3, L10). This social basis is important because scriptwriting, even more than design, relies on a commission from the client. Consequently, one main *obstacle* is again represented by budget and timeline for completion. The world of cinema revolves around budgets for stories and "economic imperatives" (L3, L4, L8, L11) writers cannot possibly escape. Other difficulties have to do with inspiration blocks (L7, L8) and the complexity of gaining a comprehensive view of the entire work (L8, L10).

Unlike art and closer to science, scriptwriting requires a certain discipline and the *time and place* for work tends to be well established: writing almost daily (L4, L6), for at least 3 h (L1, L6), in an office (L7). This leaves space also for particular routines some have, for example that of writing in cafes (L1) or changing the program very quickly to foster spontaneity (L12). The *stages of doing* are also generally preset and they are learned as part of the craft. The process begins with a general idea, usually offered by the client. For some this idea needs to be quite structured (L5, L6), others enjoy more freedom at the start (L1) but in any case ideas are always worked closely with the film director (L11). After the topic of the scenario becomes clear, a stage of documentation is necessary, during which writers interview people and read books (L5), watch documentaries relevant to the subject (L12) and at times get to do some "fieldwork" (L10). Again, depending on the style of work, documentation can end up with a general plan or simply with material for further elaboration. A central phase of intense writing starts from documentation and leads into the editing stage. Writing "enormously" (L6) and using plenty of notebooks to put down ideas, sequences, even dialogs (L1) is crucial during this period. The outcome is usually very long and needs to be simplified and organized (L12), something that invites plenty of rewriting and revisiting. In the end, the plan (or sequence of episodes) is a "transitional object" (L10), perfectible and open to change. Finally, the editing part can take a long time in itself and it is when the dialogue and details for each scene are clarified (L4). Plenty of *work procedures* facilitate the task of writing a script. Among the "tricks of the trade" some mention writing a personal diary for the main characters (L1), or simply a narrative in first person (L2). Always having a notebook with you and taking a lot of notes is a requirement as well as taking regular breaks from the script to gain some detachment (L3). *Working materials* are relatively few in this case, primarily notebooks and the computer (L1). Interestingly, some love to write by hand (L7) and use the computer just for later transcribing or corrections (L10), whereas others put down on paper only the general plan (L9, L11).

OBSTACLE		BUDGET AND TIMELINE		INSPIRATION BLOCK	BALANCING DETAILS VERSUS HAVING A GENERAL VIEW		
DOING	IMPULSION TO EXPRESS TO WRITE TO CREATE	GENERAL IDEA	DOCUMEN-TATION	INTENSE WRITING	REWRITING REVISING	EDITING	FINAL SCRIPT
UNDERGO MATERIAL	UNDERGOING BEFORE DOING		UNDERGOING BEFORE DOING	LOGIC/RULES OF WRITING STORYLINE/CHARACTERS IMPOSE THEMSELVES			UNDERGO FINAL RESULT
UNDERGO SOCIAL	LIFE EXPERIENCE BOOKS AND FILMS	LONG TALKS WITH THE DIRECTOR			DIRECTOR, CLOSE FRIENDS AND COLLABORATORS		DIRECTOR AND OTHER CREW
EMOTION				DOUBTS, STRESS, ANXIETY, JOY, JUBILATION			SATISFACTION

FIGURE 5 | Schematic representation of creative activity in the case of scriptwriters.

The *undergoing before doing* for scriptwriters is largely based on personal life experiences and the enjoyment of books and films (L3, L5, L6, L7). Scriptwriters have habitually the attitude of a "hunter in the forest," always on the alert, always taking notes (L10). Frequently, the starting point is connected to one's own history, the things seen as a child, the lived experience and the people one knows (L6). At the same time, writers are "permanently nourished by the spectacle of the others" (L8). In the end, a scenario is always the "fruit of collaboration" and "it is never a solitary work, even if sometimes you work alone" (L11). Forms of *social undergoing* start with the client: the film director and producers. Writers need to comply with their wishes (L2), understand their vision (L5) and this requires constant interactions for establishing and maintaining a "common ground" (L1, L8, L9). "The relationship with the director is at once something intimate and devouring" (L10). In the end, the director's views matter and he or she is the one to say when the script is "ready to go" (L1, L4). Close collaboration can also exist with fellow scriptwriters as, quite often, a script is a "shared work" (L5). A "ping-pong game" (L2) of "back and forth" (L10) starts between collaborators and their input is valuable because it can give perspective, "prevents one from turning around in one's own madness" (L3). Friends are sometimes also used for this purpose (L1, L5, L7). By the end, everything is "co-written" between fellow writers and there is no way of knowing anymore who wrote what (L8). The relation with critics and the public can bring joy or suffering but rarely affects the work directly (L1, L6). Recognition is desired (L1) but the film industry is often plagued by jealousy and competition (L6) and too much praise or too much criticism can be equally blocking (L7). On the whole, there is rarely a real appreciation in society for the role and contribution of the scriptwriter and this is experienced by many as "humiliating" (L10).

Although not working with physical objects like artists, designers, and scientists, writers are by no means free of *material forms of undergoing*. On the contrary, these are equally present and directive in shaping the work flow. There is a materiality of the script and a moment in the process where it seems to take "a life of its own" (L2), when "the logic of the story is gradually unfolding" (L3). This moment is essential and needs to be captured because it signals that the project is on the right track (L1) and is taking the lead (L11). The characters have an important part to play in this unfolding given that, as they develop, they gain in power, become "alive" (L6) and start following a logic that imposes itself (L7). In a conflict between structure and characters, it is the characters that usually win (L12). This is part of the "laws" of dramaturgy – norms that generally guide the construction of the story (L5). Ultimately, another constant form of material undergoing has to do with re-reading the script, normally out loud (L8, L10), and sometimes by acting or miming the scene (L10).

The *emotional background* of scriptwriting is extremely mixed. Whereas making the plan can be both exciting (L9) and frustrating (L8), during the writing episodes a combination of pain (L5), anxiety (L11, L12), depression (L8), anguish (L4) and at times "intense joy" (L1), happiness and jubilation (L2), takes center stage. However, as repeatedly acknowledged, "when you love cinema there is always a pleasure to some extent" (L11). This feeling is exacerbated toward the end when relief and accomplishment are equally felt (L9); when everything is done and everyone is happy: "for 48 h I am the happiest woman on Earth!" (L1). Indeed, this emotional state is also an important criterion to evaluate the final outcome – the script is finished when satisfaction outweighs frustration (L7). This happens though after a continuous *cycle of doing and undergoing* when "you write something, you have it read, you re-write, you have it read" (L5), a back and forth movement (L11) of a specific nature and yet described by creators from all domains. The *experience* of scriptwriting makes no exception and confronts the creator everyday with his or her limits (L1), but, just as in every other case, "without contradiction there is no fulfilment" (L5).

CREATIVE ACTION IN MUSIC COMPOSITION

In many regards, the group of composers shares similarities with other "artistic" domains (see **Figure 6**). To start, their *impulsion* is defined by a need to create music (M8), to work on a song (M2) or a particular musical element (M6, M8). As is the case with other

FIGURE 6 | Schematic representation of creative activity in the case of composers.
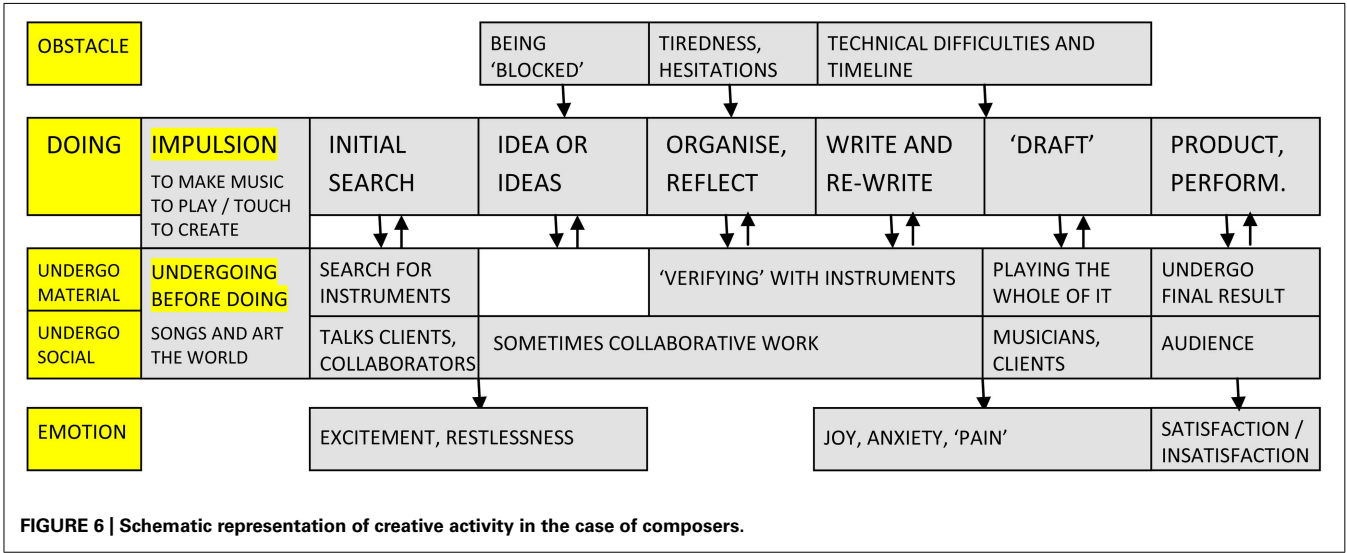
artists, this work is seen as a "necessity" (M6), an inner "creative force" that imposes itself on the composer (M11). There is also a more precise need to "touch" and play an instrument (M2) and to be original, not necessarily in doing something never seen before (M6, M7), but something unknown to the author (M8, M9, M11). The nature of the *obstacles* is also shared with other domains. First comes the situation of being "blocked" (M1), the anxiety of the "blank page" (M7), when things stop being "fluid" and become difficult (M6, M10, M11). Then come tiredness (M1), hesitations, and constant questioning of the work (M6). Finally, in accordance with designers and scriptwriters, there are also timelines to be considered because most pieces of music are in fact commissioned by clients.

Similar to other artists, musicians as well discuss the irregularity of creation in terms of *time and place*, the fact that you cannot have a strict schedule (M1, M4, M8, M9) and depend on a specific state of "disponibility" (M6). Whereas some like to work in different places (M6), others have a studio (M10, M11). A particularity for this group has to do with the number of people who claim to be working at night (M4, M6, M9, M10, M11). The *stages of doing* usually start with an initial search. This is the case because very often for composers, even when working for a client, the preliminary guidelines are quite general (M7, M8). For this reason, composers are left to establish their own "sound palette," looking for "sound actors" that will later be placed in a corresponding "script" (M4). Writing them down, the composer is then waiting for an "idea" (M8), for a "click" (M4). This is the second stage, when insights emerge out of an "accumulation of things" and one idea attracts another (M1, M3). More often than not, musicians work with ideas in plural, rather than one single "vision" (M8), as compositions have a time dimension. Given that there are many ideas or themes to work with, a moment of organization and reflection becomes necessary: distancing yourself a bit (M1) and trying to make a plan (M7). The writing and re-writing of compositions is of course a central stage in the production process, a technical phase (M8) when things become more "precise" and new ideas can spur from the process of writing itself (M6). Just as in the case of designers, composers often work on several versions of a song (M9). The "draft" stage is equally dynamic because editing takes place as the author listens to the work during rehearsals (M6, M11). Even in the final product phase, small changes can be made while the song is transcribed (M7) and the end truly comes when the music is officially recorded or played (M10). The whole process can be defined as a "progressive concretisation" (M7), from conceptualization to final performance (M6).

Work procedures guide activity and relate mainly to simplification (M1), varying instruments (M2) and themes (M3, M9), reposition and juxtaposition (M3), repetition (M3, M9), decomposition (M2), combination (M7, M9), etc. Many of these procedures are facilitated by the use of technology that permits the integration of effects, insertion, mixing, dividing, synthesizing, modulating and multiplying segments, compressing and decompressing, cutting and reorganizing (M5, M9, M11). It comes as no surprise that, among the *material tools* used by composers, computers, and mixing software are a priority (M1, M3, M4, M9, M10). However, instruments are also mentioned, along with more classical equipment: microphones, speakers, tapes, and even the traditional paper and pencil for writing music (M7).

Before getting to use these specialized tools though, and in order to be able to write music, a period of formal training is needed, sometimes starting from teenage years with playing certain instruments (M4, M9). The *undergoing before doing* is, in this case as well, continuous and "learning never ends" (M8), an integral part of it being listening to music of diverse genres and origins (M6, M7). Old songs offer inspiration (M1, M9) and excellent starting points for the initial search phase (M5). The world more generally is another great source of inspiration, and composers "love to look at things" (M5), to go to the cinema (M4), to read, paint and go to concerts (M6). They are often very curious, "receptive" (M7), like a "sponge" in absorbing their surrounding (M5) and adding things to the "reserve of what has been lived" (M8). Their relationship to the material world is particularly strong and reveals various forms of *material undergoing*.

To begin, musical notes and instruments have a materiality that is impossible to ignore. Notes are "compulsory" (M3) and instruments offer a framework of possibilities (M6). There is a very "primitive, tactile" feeling for all those who get to work with music instruments (M8), where the "immediacy" of the instrument (M9) needs to be mastered, practiced, "domesticated" even (M12). Another form of undergoing is embedded within the work process when composers write and then listen back, deciding what to do next with the material (M1, M2, M3, M9). This feedback is alimented by a "need for contact," a need to "verify" (M7) one's intuitions. Accidents play also a role in this process, and they are "artistically interesting to have" (M2, M12). In the end, music is "physical, it vibrates in the body" (M3) of the composer in ways that gradually become internalized, constituting an inner "voice". On the other hand, music is also a social enterprise, and *social types of undergoing* link composers to clients, colleagues, interpreters/instrumentalists, and the larger audience. Clients impose particular constraints (M1) and can be hard to please so one has to work "in reaction" to propositions, trying to always bring a personal note (M7). With interpreters/instrumentalists the relation can also be fruitful but difficult. Compromises need to be made and, at times, complicated pieces are simplified (M6). With other colleagues there is a constant exchange of ideas and reflections (M4, M5, M12). For some, being a musician means working "in a group" (M9), where both success and failure are shared (M6). This helps to perfect one's own technique because "composition as such is not taught, it is learned through encounters" (M11). Finally, the public is the final recipient of the work so the appreciation of others is part of the success of the composition (M4, M9) and critical feedback needs to be taken into account (M1, M11).

The final satisfaction or dissatisfaction with the outcome is relative to the public but also to the composer's own evaluation of the result according to compositional criteria (M6) such as "coherence," "good form" and "continuity" (M9). However, many respondents admit to never being truly satisfied (M7, M8) whereas others allow themselves to feel exaltation (M3) or happiness (M11). Other *emotions* characteristic for this work are the initial excitation and incertitude (M1), followed by different

emotional states while working: plenitude (M1), pleasure (M2), "erotic sensations" (M3), anxiety (M7), "romantic sadness" (M8), jubilation or melancholy (M10), etc. These reactions come as a consequence of the particular ways in which *doings and undergoing interact*, their specific moments of "back and forth" (M10, M12), alternation between "zoom and distance" (M6), between gesture and listening (M5). Everything in music composition seems to be under the logic of "groping around" (M8, M9), of making and re-making that lead to a "spiral" of progress from one stage to the next (M6). What is interesting for the composer is "what is born out of the interaction with the tool, with the instrument, with the context" (M12). The *experience* of music creation is constituted directly by interaction and resistance which are necessary to "measure the value of one's inspiration" (M10).

DISCUSSION

The present article aimed to make a contribution toward developing an action analysis of creative activity. Grounded in pragmatist accounts of action, the framework proposed here focuses on the permanent exchange between a creator's "doing" and the reaction it generates from the social and material world, the awareness of which is defined as "undergoing." This broad perspective became gradually specified and resulted in the elaboration of schematic representations of creative activity in all five domains under investigation. Important to note, these schemas reflect *content-specific aspects* of activity for each field and not general and abstract creative processes. As such, depictions both confirm and expand previous results from the literature.

In *art*, for example, Mace and Ward (2002) proposed a basic succession of interconnected stages in the form of artwork conception, idea development, making the artwork and finishing the artwork/resolution. Similar moments in the artistic process are depicted in **Figure 2**: the general vision can be related to artwork conception, the documentation and reflection stage to idea development, making the artwork corresponds to the first sketches and their testing whereas finishing the artwork leads to the final moments of the "draft," final product or series. Both conceptions seem to intersect in the claim that "the genesis of an artwork arises from a complex context of art making, thinking, and ongoing experience" (Mace and Ward, 2002, p. 182). In design, some current models of the creative process – such as the A-CM (Bonnardel, 2000) or the F-B-S model (Gero, 1998) – try as well to integrate components related to situated cognition. In addition, Tan and Melles (2010) have recently approached design

work through the lenses of activity theory. Their description of observed activities as "for the most part dynamic, iterative, and opportunistic" (Tan and Melles, 2010, p. 474) corroborates previous descriptions of design activities as opportunistic (see, for a review, Visser, 1994) and matches the type of processes comprised in stages like "first sketches" and "perfecting the form" (see **Figure 3**).

Investigations of *scientific* creativity for the most part either confirmed the classic four stages model of preparation, incubation, illumination and verification (see Sriraman, 2004), or enlarged it (see Busse and Mansfield, 1980). The model we propose here departs in a significant way from this traditional conception. Whereas the idea/illumination moment seems to be consistently mentioned by most scientists, the process is focused more on incremental progress from experimentation to mathematical formalism and then again experimentation. The same kind of gradual development was proposed by Csikszentmihalyi (1996) in relation to creative *writing*. Rather than one great moment of illumination, the author suggested a more continuous activity of generating "smaller" ideas, then connecting and revising them. The stages of "intense writing," "rewriting/revisiting," and "editing" reflect this insight. At last, descriptions of *music composition* by Bennett (1976) are similar to the ones proposed in **Figure 6**, starting from a "germinal idea," continued with brief sketches, a first draft, elaboration and refinement and then completion. What action analysis brings to this field, though, is a greater acknowledgment of the role of social and material factors for composition. Kaschub (1997) once stated that restrictions and limitations play a key role in music creation. The origin of these restrictions and their result are two fundamental concerns for activity theory.

One of our declared aims in selecting five creative domains and using the same action coding frame for all the groups was to uncover possible patterns of similarity and difference between them (in agreement with current understandings of creativity that consider both its domain-general and domain-specific aspects; Lubart and Guignard, 2004; Baer and Kaufman, 2005). Such patterns are briefly presented in **Table 3** in terms of the main codes of impulsion, obstacle, doing, undergoing (material and social), and emotion. What can be immediately noticed is that, against a common presupposition that science would stand out and that design would "mediate" between it and the other three more "artistic" domains of art, scriptwriting, and music, we are confronted with a *patchwork of similarities and differences* between domains regarding each of the six criteria.

Table 3 | Summary of patterns in creative activity in the five domains.

	Art	Design	Science	Scriptwriting	Music
Impulsion	**Create/express**	**Create**/solve	Solve/curiousity	**Create/express**	**Create/express**
Obstacle	**Tools/material**	Budget/**tools**	**Tools/material**	Budget/time	**Tools**/time
Doing	**Idea/work/idea**	**Idea/work/idea**	Work/idea/work	**Idea/work/idea**	**Idea/work/idea**
Undergo (MAT)	**Physical prop.**	**Physical prop.**	Laws/norms	Laws/norms	**Physical prop.**
Undergo (SOC)	**Colleagues**	Client	**Colleagues**	Client/**colleagues**	Client/**colleagues**
Emotion	**(DIS)Satisfaction**	**(DIS)Satisfaction**	**(DIS)Satisfaction**	**(DIS)Satisfaction**	**(DIS)Satisfaction**

For impulsion, indeed, the three "arts" can be grouped under a general need to create and express, which somehow differs from a scientist's urge to solve and learn about the world, designers sharing here a bit of both. Obstacles though bring art and science together in facing difficulties related to materials and tools; the problem of adequate tools is present also for designers and musicians. Budget and time are more pressing issues for scriptwriters, and resonate as well with the budget constraints of designers and the deadlines faced by composers. Across all domains, the "inspiration block" can be a common obstacle. The "doing" element reorders the five domains, this time along the lines of a dichotomy between scientists and other creators. If in science a dynamic seems to be set in place in which a general problem is examined, this work leads to an idea and the idea is developed in subsequent work. Artists, designers, scriptwriters, and composers all mentioned the idea, "vision" or client's brief as the starting point. This initial input is processed and then further ideas emerge. Material forms of undergoing revolve mainly around the physical properties of objects for those domains which are immersed in the material world (art, design, and music), and around the laws and norms of the physical or dramaturgical universe for science and scriptwriting, respectively. From a social perspective all creators, independent of their particular discipline, emphasized the necessity of relating with others, exchanging ideas and being evaluated. The figure of the client is paramount in design and important for scriptwriters and composers as well, whereas colleagues or peers are regular interlocutors in science and art. In the end, the emotion dimension did not yield any significant differences between creators and it seems that, irrespective of domain, creative activity is marked by ups and downs, by oscillations between euphoria and depression, between satisfaction and dissatisfaction with one's work.

Such findings are important for the educational field. To begin, they point to the fact that educating children for creativity should consider the domain specific features of creative action. It is certainly the case that, at school, children are not in the position of acknowledged artists or composers during their art and music classes, nor are they scientists who could make significant contribution to a domain while studying math or physics (or at least the probability is very low). It is widely accepted today that acts of historical or Big C creativity require many years of training, something formalized by Hayes (1989) as the "ten-year rule." A crucial question, however, is what exactly happens during these years of training, many of which take place as formal schooling in an educational setting (see the example of scientists in our study). Also, how can this period of preparation – whose length again varies depending on domain – be most fruitfully organized to facilitate high-level creative expression? Moreover, because practice or preparation work are actually continuous for creators in most fields of activity (and certainly in the five domains studied here), we need to consider creative action as equally continuous and not taking place only when (and if) a highly celebrated outcome is actually produced. Under these circumstances, educators should focus on the nature and quality of what we called here "undergoing before doing" – the stage of preparing oneself for creative activity on the long run but also before working on particular projects. Ideas about what motivates recognized creators to work (found under "impulsion") can suggest the kinds of needs and impulses we should encourage in children, from an early age. Finally, knowing about the stages of doing in particular domains can help us structure our teaching of artistic and scientific disciplines and make good use of those material and social conditions that facilitate creative expression (adequate tools, social recognition for one's work, etc.).

In the end, it is also important to realize the shortcoming of the present research. To start, we reported findings here from a relatively small number of participants (although adequate for a qualitative investigation) and all belonging to a particular cultural context. We can also question to some extent the trustworthiness of self-report data, even though self-report scales are quite popular in creativity research and Hocevar (1976, p. 455), in another context, claimed they are "perhaps the most easily defensible way to identify creative talent." But the most notable limitation, from a theoretical perspective, relates to our effort of translating theoretical assumptions into research devices. Going back to the psychology and philosophy of John Dewey, what transpires from all his writings is an effort to transcend dichotomies, especially those between self and world, and artificial segmentations between cognition, affect, motivation, and volition, all understood as building blocks of human experience. For analytical purposes though, segmentations had to be made, even temporarily, in order to end up with a broader, more dynamic and unitary picture of creative activity. While a certain dynamism was introduced by relating the doing of the creators and the obstacles they face to material and social forms of undergoing, on the whole, the schemas presented above do not contain many feedback loops between stages, as other models rightfully do (e.g., Mace and Ward, 2002). This limitation can be accounted for by the nature of interview data and the fact that interviews alone only offer verbal reconstructions of creative work and are thus subject to narrative formats (progressing from "introduction" to "conclusion"). Subsequent studies, currently conducted by the authors, strive to overcome this shortcoming by adding an observational, longitudinal element to interview accounts.

In summary, the present study aimed to develop an action framework for creative activity, one that strives to be more comprehensive than previous cognitive models of the creative process. This framework, both a theoretical and methodological tool, does not disregard earlier findings from the cognitive tradition but tries to integrate them into a more contextual perspective which reunites the psychological and behavioral aspects of creation with its material and social effects. As such, it strongly connects with contemporary "extended mind" theories (Clark and Chalmers, 1998) and a vision of cognition as distributed, external and situated. Applying this theoretical perspective results in "local" models that respect the particularities of each creative field, while enabling comparisons between them. These local models can also be very fruitful for our efforts to enhance creative expression in different domains, in educational settings and beyond.

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Environmental influences on neural systems of relational complexity

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Constructivist learning theory contends that we construct knowledge by experience and that environmental context influences learning. To explore this principle, we examined the cognitive process relational complexity (RC), defined as the number of visual dimensions considered during problem solving on a matrix reasoning task and a well-documented measure of mature reasoning capacity. We sought to determine how the visual environment influences RC by examining the influence of color and visual contrast on RC in a neuroimaging task. To specify the contributions of sensory demand and relational integration to reasoning, our participants performed a non-verbal matrix task comprised of color, no-color line, or black-white visual contrast conditions parametrically varied by complexity (relations 0, 1, 2). The use of matrix reasoning is ecologically valid for its psychometric relevance and for its potential to link the processing of psychophysically specific visual properties with various levels of RC during reasoning. The role of these elements is important because matrix tests assess intellectual aptitude based on these seemingly context-less exercises. This experiment is a first step toward examining the psychophysical underpinnings of performance on these types of problems. The importance of this is increased in light of recent evidence that intelligence can be linked to visual discrimination. We submit three main findings. First, color and black-white visual contrast (BWVC) add demand at a basic sensory level, but contributions from color and from BWVC are dissociable in cortex such that color engages a "reasoning heuristic" and BWVC engages a "sensory heuristic." Second, color supports contextual sense-making by boosting salience resulting in faster problem solving. Lastly, when visual complexity reaches 2-relations, color and visual contrast relinquish salience to other dimensions of problem solving.

Keywords: event-related fMRI, heuristic processing, prefrontal cortex, reasoning, color perception, relational complexity, visual contrast, constructivist learning

INTRODUCTION

The human brain collates, integrates, and binds basic sensory inputs that result in our capacities to think, reason, and perform at high levels (Waltz et al., 1999; Kalbfleisch et al., 2006, 2007). It processes with great efficiency in complex environments such as natural scenes, virtual worlds, gaming environments, athletics, the visual and performing arts, and in the classroom, to name a few. Studying learning and performance in those contexts means accepting a high degree of variance in the assessment and evaluation process. Contemporary learning theory (e.g., constructivism) highlights the central role of both the learner's meaning making and his or her interaction with the environment in creating knowledge. Constructivism is a learning theory that contends we construct knowledge best by experience and

that our environment and the context it provides is a central determinant in the quality of our learning. It holds within it such principles as "scaffolding," "the zone of proximal development," and the "genetic epistemology" that have influenced the fields of educational psychology and the learning sciences for decades (Vygotsky, 1928; Bruner, 1960, 1990; Piaget, 1970). Educational psychology has held a long interest in determining more specific heuristics that would increase our pragmatic capacities to implement constructivist principles of learning (Phillips, 2006). In past, neuroscience has examined the means by which experience impacts gray matter change (Diamond et al., 1975, 1976; Quartz and Sejnowski, 1997), however, there is a paucity of evidence for the consequences of specific environmental influence on functional neuroplasticity during higher-level reasoning.

A better understanding of how the brain achieves efficiency with input from the physical environment will contribute insight to help education researchers, designers of architecture, technology, and curriculum, and teaching practitioners gain a more practical understanding of constructivist principles so that they can accommodate and apply them in practice with greater precision.

Early experiments exploring aspects of visual complexity such as pattern, shape, color and contour determined that features of symmetry and context reduce the psychological perception of complexity (Chipman, 1977). Relating to this, we aim to understand the neural basis of some of these processes during problem solving and how or why they may support constructivist learning. The key question is how do we identify and trace neural systems of reasoning that are engaged during psychometric tests and controlled in neuroimaging paradigms to better appreciate how these systems evolve and support more naturalistic knowledge about cognition (Pylyshyn, 1999; Mahon and Caramazza, 2009; Schwarzkopf et al., 2009)? Specifically relating to our experimental design and the opportunity to connect a neural result with a meaningful outcome for education and measurement, we aim to understand more about how and/or why certain visual properties or heuristics are enlisted during matrix reasoning because it serves as a proxy measure of intellectual capacity (Kalbfleisch, 2004). We employ the word "heuristic" to represent how visual and reasoning systems function together to compute "empirical approximations" (Gershman et al., 2012) or create "frames" that assist in simplifying context during ambiguous or complex reasoning conditions (De Martino et al., 2009). De Martino et al. (2009) highlight how affective heuristics influence rational decision-making. In a similar fashion, to examine how qualities of visual perception influence relational complexity (RC), we apply black-white visual contrast (BWVC) and color to an ecologically-valid model of non-verbal matrix reasoning. Our model is ecologically valid in two ways, one, for its psychometric relevance, and two, for its potential to link the processing of psychophysically specific visual properties with various levels of RC during reasoning. The role of these fundamental perceptual psychophysical elements is important because non-verbal psychometric instruments such as matrix reasoning tests assess one's aptitude from how well one problem solves within these seemingly context-less exercises. In doing this, we stand to gain a better understanding of how specific stimulus properties converge to influence general neural systems affiliated with human reasoning (Christoff and Owen, 2006). This experiment is a first step toward examining the psychophysical underpinnings of performance on these types of problems.

Recent letters postulate on how to reconcile results among neuroimaging studies of reasoning (Brzezicka et al., 2011) and the potential application of this knowledge for training, pedagogy, and intervention (Houde, 2008). It stands, then, that matrix reasoning (a measure of intellectual capacity that we can parametrically vary in an experimental context) correlates with some forms of academic achievement (evidence of behavior in an important real-world setting, the classroom), and presents a ripe opportunity to explore how specific visual properties from complex real-world environments, may impact performance potential across a range of individual differences. Underscoring the relevancy of this idea, emerging evidence asserts there may be a predictive validity in the relationship between intelligence and the sensory discrimination of visual motion (Melnick et al., 2013).

In keeping with this, the evolutionary importance of visual contrast on perception (Kelly, 1977), illustrates that some aspects of early visual processing such as color and visual contrast are important and central to survival (Bowmaker, 1998; Gerl and Morris, 2008). Studies to date that examine how the visual system is modulated by specific properties such as color or motion are often explored within experiments on perception that have no overt problem solving requirement (Shipp et al., 2009; Cardin et al., 2011). Here, we examine these properties within the construct typically characterized in the superior frontal lobes called "RC," "the number of related dimensions, or sources of variation, that need to be considered simultaneously in order to arrive at a correct answer" (Halford and Wilson, 1980). RC is both a perceptual process and a metric of visual complexity that supports mature reasoning capacity (Halford et al., 1998; Christoff et al., 2001; Kroger et al., 2002; Crone et al., 2009; Wendelken and Bunge, 2010). It is a systematic heuristic that accounts for how visual properties scale in complexity and, for this reason, provides an ideal method for exploring the means by which visual properties from the environment such as color and visual contrast influence higher-level reasoning and choice. In general, relational integration relies only in part on the executive resources of working memory (Cho et al., 2007; Badre, 2008) and attention (Posner and Petersen, 1990). Previous experiments have shown that reasoning involves, but is separate from working memory (McCarthy et al., 1994; Owen et al., 1996; Bechara et al., 1998; Ruff et al., 2003; Cowan et al., 2012). In fact, functional nuclei are distributed throughout the human frontal lobes that enable diverse executive functions (Duncan and Owen, 2000), though they appear uniform to the human eye. In this paper, we give central focus to RC, leveraging its parametric properties to scaffold between and among the visual properties color and BWVC during matrix reasoning.

Color as a visual feature in both low-level and high-level vision has been well-corroborated by converging neurophysiological, neuropsychological, and behavioral evidence (Livingstone and Hubel, 1987; Bartels and Zeki, 2000; Tanaka et al., 2001; Wade et al., 2002; Shipp et al., 2009; Zeki and Stutters, 2013). Color facilitates object perception and also recognition, but has also been shown to play a significant role in scene segmentation and visual memory (Tanaka et al., 2001; Gegenfurtner, 2003; Werner and Chalupa, 2003; Peelen et al., 2009). Brain areas necessary for color perception and integration include several areas in the visual cortex such as ventral occipital and temporal extrastriate areas (Wade et al., 2008), and sub-regions of the occipital and parietal lobe (Vaina, 1994; Wade et al., 2002) in fusiform gyrus, collateral sulcus, and lingual gyrus (Bartels and Zeki, 2000; Claeys et al., 2004; Morita et al., 2004). Thus, it is important to determine when color serves basic perception and when it is involved in higher level processing. Important to this experiment, selecting color on its own in a choice task does not activate the superior or middle frontal cortices (Rowe et al., 2005). Whereas, RC is supported by activity from the superior and lateral areas of

the prefrontal cortex, known collectively as the rostrolateral prefrontal cortex or RLPFC (Christoff et al., 2001; Kroger et al., 2002; Koechlin and Summerfield, 2007; Bunge et al., 2009).

To summarize, color perception and RC are separately accounted for in the neuroimaging literature, but how the brain integrates properties of visual information from the environment such as color and visual contrast into the RC process and higher-level reasoning in general is unknown.

On a practical level, several cognitive neuroscience studies have based neuroimaging tasks on problems adapted from the Raven's Progressive Matrices Test (RPM; Raven, 1938) to document reasoning and RC during fMRI, functional magnetic resonance imaging (Prabhakaran et al., 1997; Christoff et al., 2001; Kroger et al., 2002; Crone et al., 2009; Baldo et al., 2010). The RPM, a psychometric assessment of intellectual capacity, is designed to evaluate the ability to form perceptual relations and to reason by analogy independent of language, ethnicity, disability, or formal schooling. As such, it offers a way to examine consilient real-world visual perception and its influence on decision-making. Here, it is a logical extension to use an RPM-like matrix task to parametrically examine the impact of color and visual contrast on RC. This self-paced fMRI study employs RPM-like stimuli designed to parametrically vary complexity (0, 1, 2) within no-color line, BWVC and color conditions (**Figure 1**).
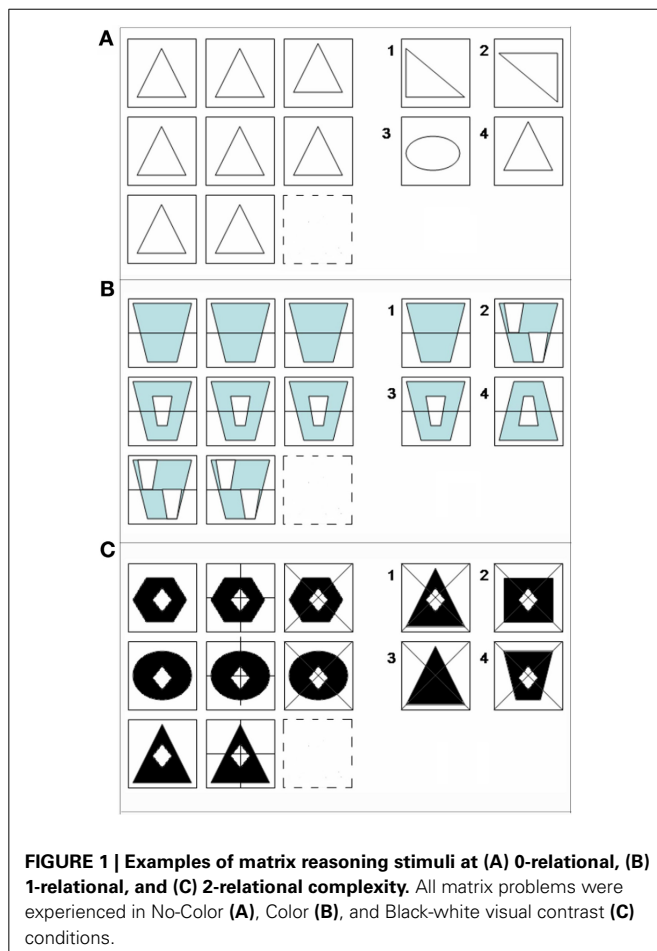

FIGURE 1 | Examples of matrix reasoning stimuli at (A) 0-relational, (B) 1-relational, and (C) 2-relational complexity. All matrix problems were experienced in No-Color **(A)**, Color **(B)**, and Black-white visual contrast **(C)** conditions.

Parametrically varying visual properties at the same level of reasoning complexity provides us with a strategy to document the sensory contributions to reasoning between each kind of property. In turn, parametrically varying the complexity level within each visual property permits us to characterize the neural systems supporting reasoning among cognitive levels of demand within each type of stimulus context. We hypothesized that color and visual contrast (1) contribute additional sensory load to relational reasoning resulting in extended behavioral reaction times, and (2) that those differences are observable and dissociable in the visual and prefrontal cortices. Thus, hypothesizing that real-world visual properties play a supportive role in relational reasoning, our open question was under which levels of complexity and to what extent do properties of the visual environment influence the RC system in the frontal cortex to enable successful decision making and choice?

To our knowledge, this study is the first to document the convergence of color perception and RC during a self-paced reasoning task, representing one example of how perceptual processes enable higher level cognition in the context of a task format commonly used to assess problem solving skill and general intellectual capacity.

MATERIALS AND METHODS

SUBJECTS
Participants included 34 neurologically healthy volunteers (11 male, 23 female; mean age = 24.2 years, range 18–46 years, $SD = 7.5$). All volunteers were right-handed with a mean score of 86.48% on the Edinburgh Handedness Inventory (Oldfield, 1971). None reported history of color-blindness. All participants gave written informed consent prior to participating in the experiment approved by the Human Subjects Research Board (HSRB) of George Mason University, Fairfax, VA. Each subject's participation consisted of one visit to the laboratory and involved three parts: a confirmatory MRI safety and compliance screening by the technologist, a brief practice session with the task using problem trials separate from the problems they solved in the scanner, and ∼1 h in the MRI scanner including time for the subject to be comfortably positioned in the scanner, to acquire structural brain scans needed for data analysis, and to have the participant perform three runs of the functional task described below.

TASK DESIGN
The color relational complexity task (CRC) is a self-paced, event-related design incorporating 3×3 matrix reasoning problems missing the bottom right figure in No-color line (NC) (**Figure 1A**), Color (**Figure 1B**), and BWVC conditions (**Figure 1C**). The event-related design prevents an attention confound as the participant cannot anticipate when the next trial will appear. The task is self-paced allowing the participant to solve each problem at their own speed, but the presentation of new trials following the one just solved were jittered at intervals based on the 3s repetition time in the scanning protocol for fMRI (3, 6, 9, 12, 15 s). This jitter controls for any carryover effect of the blood oxygen level dependent (BOLD) signal, securing the opportunity to timelock the specific BOLD response to the particular time point when the subject solved each problem trial.
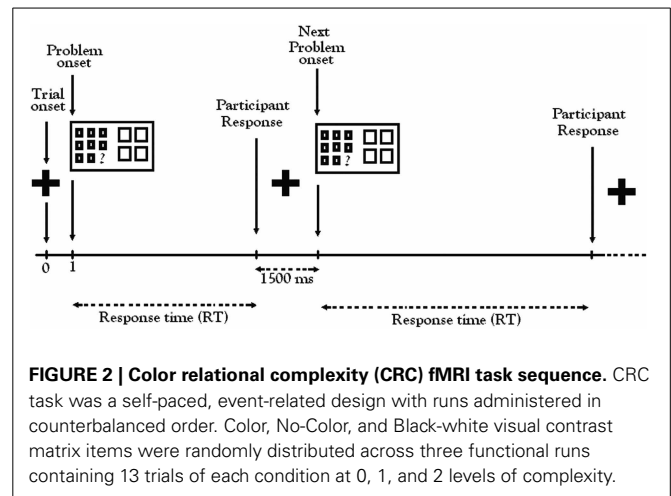
Three levels of complexity (0, 1, and 2) are defined according to the original definition as the number of variations in a visual matrix stimulus that are simultaneously processed during reasoning (Halford and Wilson, 1980). To solve, participants consider the relationships among 8 of 9 provided pieces of the matrix in the trial and select the correct answer from four choices provided. To prohibit learning and fatigue confounds, the experiment consisted of three runs presented in counterbalanced order. Each run, ~14.5 min in length, contained 13 trials at 0-, 1-, and 2-relational complexity for Color, NC, and BWVC for a total of 9 conditions presented in random order (randomized in an Excel-based program to optimize randomization). Zero-relational problems contained no change in relationship between rows or within columns of the matrix and no relational processing was necessary to solve (**Figure 1A**). One-relational trials are defined by a single change between rows of the matrix (**Figure 1B**). Two-relational trials are defined by two changes, both between columns and within rows of the matrix (**Figure 1C**). Items were either drawn in no-color line (NC), filled with black and white (BWVC), or filled with light blue (Color), a color universally perceived by individuals with typical color perception as well as those with most common forms of color blindness (Abramov and Gordon, 1994; Deeb, 2004). NC conditions provided a baseline control and validation of previous studies of RC using these item types. BWVC conditions provided a control for Color conditions, permitting us to examine the unique contributions to sensory and/or cognitive processing from each visual property.

Prior to their functional magnetic resonance imaging (fMRI) session, participants performed a practice test with samples of trials at different complexity levels to avoid a learning confound. In the MRI, they had a brief practice with the button box, using their right hand index, middle, ring, and small fingers to press one of four buttons corresponding to their choice. Problem trials were presented from a computer and back-projected through a waveguide onto a screen located in the back of the MRI scanner bore. Visual images were viewed from a mirror mounted on the head coil above the participant's head.

During the fMRI experiment, participants were alerted to the beginning of each trial by a visual cue (a 1500 ms fixation cross, "+") followed by a matrix problem (**Figure 2**). Working at their own pace, participants indicated their choice by pressing one of the four buttons on the button-box in their right hand. For each trial, the time from start of the problem to the response defined the response time (RT). The random order of trials and conditions in each run created sufficient variability in the RT to prevent autocorrelation of BOLD responses, the basis of the fMRI signal. After each response, participants were presented with the visual fixation cue ("+") to rest before the next trial. Participants were instructed to concentrate more on accuracy than speed.

MRI DATA ACQUISITION

Structural and functional MRI data were acquired using a 3.0-tesla Siemens Allegra head-only scanner (Siemens Medical Solutions, USA) located at the Krasnow Institute for Advanced Study at George Mason University. A CP TX/R head coil single-channel was used during data collection and head motion was

FIGURE 2 | Color relational complexity (CRC) fMRI task sequence. CRC task was a self-paced, event-related design with runs administered in counterbalanced order. Color, No-Color, and Black-white visual contrast matrix items were randomly distributed across three functional runs containing 13 trials of each condition at 0, 1, and 2 levels of complexity.

restricted with memory foam inserts to secure and cushion the head within the head coil. Functional runs were acquired using a standard BOLD (blood-oxygenation-level-dependent) gradient-echo echo-planner imaging (EPI) pulse sequence ($TR = 3000$ ms, $TE = 30$ ms, flip angle $= 70°$, $FOV = 192 \times 192$ mm^2, 64×64 voxels). Functional images covered the whole brain, collected in 870 volumes per participant over the course of 3 runs of 14.5 min each. Each volume consisted of 48 interleaved slices with 0.2 mm gap and thickness of 3.0 mm. The first three volumes were discarded in order to account for signal stabilization. The start of each run was manually synchronized with the scanner.

Structural images were collected as high-resolution T1-weighted images using a MPRAGE (magnetization-prepared rapid-acquisition gradient-echo) sequence with following parameters: ($TR = 2300$ ms, $TE = 2.7$ ms, flip angle $= 12°$, matrix size of 256×256) and additional structural images with following parameters: spin-echo axial-oblique T1-weighted structural scans of the whole brain (coplanar with functional images, 48 slices, repetition time (TR) $= 200$ ms, echo time (TE) $= 3.6$ ms, field of view (FOV) $= 192 \times 192$ mm^2; slice thickness $= 3$ mm, flip angle $= 75°$; matrix size $= 205 \times 256$).

PREPROCESSING

Image reconstruction was performed offline. The conversion of raw data completed using MRIconvert (University of Oregon Lewis Center for Neuroimaging). Data processing and analysis were carried out using the Statistical Parametric Mapping software package SPM5 (Wellcome Trust Centre for Neuroimaging, London, UK). Pre-processing included slice-timing, reorientation, and realignment using INRIAlign (Freire and Mangin, 2001; Freire et al., 2002), normalization to SPM EPI template, and spatial smoothing with 9 mm full width at half maximum (FWHM) isotropic Gaussian kernel. Motion inclusion criteria (less than 2 mm translational and less than 2° rotational movement) were met for all runs incorporated into the analysis. A high-pass filter with a cut-off period of 128 s was used to remove low-frequency drifts unrelated to the experimental paradigm.

fMRI ANALYSIS

A general linear model (GLM) was applied to the time course of activations to estimate condition effects at each voxel. In the first-level single subject analysis, the response function was modeled as an RT-based boxcar function (as described in the methods of Christoff et al., 2001) matching the onsets of the stimulus presentation time convolved with a canonical hemodynamic response function (HRF) (Friston et al., 1994). Linear contrast of estimated regression coefficients were used to compare the specific effects of each condition. The fMRI data from each participant were used to generate statistical contrasts for brain activations. Single runs of single subjects were evaluated to disqualify for activations outside of neural tissue and artifacts. The statistical parametric maps from the t-statistic of each voxel value for each contrast in first level analysis were entered into second-level group analysis. A random effects model was used to account for both scan-to-scan and subject-to-subject variability. Relevant to this experiment, random effects models assume that measured effects vary across the population and can account for inter-subject variance in the statistical analysis. This preserves opportunity to draw inferences at the group level. In the second-level analysis, one-sample t-tests were applied to the first-level statistical parametric maps for correlation analyses of each parameter with the BOLD signal corrected for multiple comparisons using false discovery rate (FDR, $p < 0.05$).

FDR is a type of Bonferroni correction suited to fMRI data analysis. A classic Bonferroni correction algorithm is too severe to apply to the multiple comparisons problem in fMRI data because of the comparison of over 30,000 individual voxels that comprise a single subject brain map. The consequences of this correction decreases Type I error rate, producing fewer false positives or increases Type II error rate. Additionally, it is not appropriate for correlated data and most fMRI data has significant correlation due to the fact that an individual's brain map is parcellated into these thousands of voxels and then binned into a larger group analysis that compounds these comparisons. Specifically, FDR controls the expected proportion of false positive values based on the observed distribution of activity making it more sensitive than the classic Bonferroni correction (Genovese et al., 2002). Here, statistical maps were generated based on the FDR correction and cluster extent sizes of more than 7 voxels identified the neural areas significant for each contrast.

ROI ANALYSIS

Region of interest (ROI) analysis was used to address our a priori hypothesis that the RLPFC would support RC within a stimulus context that included real world visual properties. To explore the signal more precisely for Color 1- and 2-relational problems (the levels of complexity robust enough to initiate neural systems that support RC), we performed both structural and functional ROI analysis. Structural ROIs were created according areas identified from previous studies that used similar paradigms (Christoff et al., 2001; Kroger et al., 2002). Analysis was done using MarsBar, version 0.41 (Brett et al., 2002). ROIs were defined using the WFU Pickatlas, the AAL, and Talairach Daemon atlases (Lancaster et al., 1997; Tzourio-Mazoyer et al., 2002; Maldjian et al., 2003, 2004). For each ROI, the MNI coordinates of the maximums of signal

intensity for each activation cluster were entered into the WFU Pickatlas to determine anatomical location. All voxel classifications were confirmed after translation from MNI into Talairach coordinates by manual visual inspection using the Talairach atlas (Talairach and Tournoux, 1988). Functional ROI analysis was performed in the RLFPC (BA6, 8, 10) and posterior areas surviving correction for multiple comparisons by creating a ROI from each maxima in the cluster analysis and masking it with spherical ROIs (radius = 10 mm) at the peaks of activation in each region cluster (Poldrack, 2007). These ROIs were analyzed statistically on a single subject and group level for statistical power for comparisons and for the finite impulse response (FIR) time course of the activations in Color 1- and 2-relational problems.

RESULTS

As a précis to reporting these results, we direct the reader's attention to a few primers that promote greater scientific understanding of neuroscience tools and methods in education and social science research (O'Boyle and Gill, 1998; Cacioppo et al., 2003; Kalbfleisch, 2008). Publications such as these educate the layreader about these tools and methods and lay plain the potential impact of neuroimaging studies to improve how we educate. In addition, to present an advanced organizer to the reader, what do the results from this experiment suggest in practical terms?

First, our main behavioral findings can be understood in two points:

(1) As expected, RTs increase as a function of complexity within each condition.
(2) Counter-intuitive to a parametric response to increased cognitive load, RT during Color 1-relation was significantly different from and less when compared with NC 1-relation and with BWVC 1-relation illustrating that color facilitates cognitive performance by boosting salience.

Second, our main physiological findings can be understood in two points:

(1) When controlling for sensory contribution, a broader, larger, and functionally distinct suite of visual areas support processing in BWVC (BA17/18/19) than for Color (BA18/19), illustrating a neural efficiency for how color primes cognitive performance.
(2) When controlling for stimulus complexity, the rostrolateral prefrontal cortex (RLPFC), the suite of areas that specifically support relational integration during reasoning, is preferentially engaged during Color RC. This is observed in a double dissociation between visual and frontal areas that engage for BWVC (working memory) and for Color (RC) (**Table 3**, **Figure 4**).

BEHAVIORAL RESULTS

Participants demonstrated a mean level accuracy of 95.7% (standard error = 0.44%). The analysis of data for systematic decrease in accuracy or systematic increase in RT from the beginning to the end of each run did not indicate a fatigue effect. Accuracy percentage and mean RT per condition were computed for each participant and averaged for each condition and complexity

level (**Figure 3**). As the task was self-paced, observed changes in accuracy between conditions were not significant. Only correct trials were included in the RT analysis. Mean RTs for each condition at each level of complexity are reported in **Table 1**.

A One-Way ANOVA with repeated measures and a *post-hoc* analysis of RTs showed a significant increase corresponding to the increase in the level of complexity within each condition [$F_{(8, 34)} = 129.93$, $P < 0.0001$] (**Figure 3**). A between comparison of both Color and BWVC with No-Color problems at equal complexity levels showed significant increase in RT for BWVC 0-relational trails ($M = 475.99 \pm 61.34$ SE, $P < 0.000$) and for Color 0-relational trails ($M = 525.58 \pm 66.99$ SE, $P < 0.000$). However, the same comparison at 1-RC level showed a significant decrease in RT for Color problems ($M = 234.60 \pm 66.02$ SE, $P < 0.04$) and no significant change for BWVC. Within 2-RC level, no significant changes were assessed between No-Color and Color or between No-Color and BWVC. A comparison between Color 0-relation and BWVC 0-relation trials did not show any significant change.

FIGURE 3 | Bar graph representation of response times associated with No-Color, Color, and Black-white Visual Contrast task itemsfor 0, 1, and 2 levels of relational complexity. ∗, indicates a statistically significant difference between conditions.
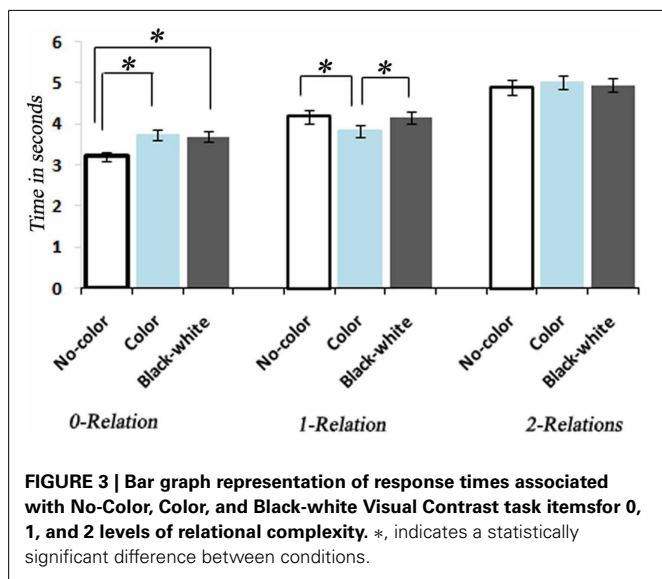
Table 1 | Descriptive statistics for category specific performance—Black-White Visual Contrast (BWVC), Color (C), and No-Color (NC) at 0, 1, and 2 levels of Relational Complexity.

Contrast	Complexity level	Mean reaction time (ms)
BWVC	2	4870
	1	4032
	0	3636
Color	2	5062
	1	3780
	0	3743
No-color	2	4991
	1	3984
	0	3138

fMRI RESULTS

Neuroimaging results include 34 participants and report activations identified through voxel-based analysis using an RT-convolved HRF. We analyzed the results for the effect of complexity level (0, 1, 2) and for the effect of each condition (NC, BWVC, and Color). For complexity level, contrasts were analyzed within and between conditions by evaluating 1-relational vs. 0-RC and 2-relational vs. 1-RC. For the effect of each condition, contrasts were performed between conditions at equal level of complexity. All neuroanatomical results are reported in **Tables 2**, **3**. To facilitate the reading of the prose, neuroanatomical areas are referred to in the convention of Brodmann Areas, a standard "shorthand" for associating neuroanatomy with function (http://en.wikipedia.org/wiki/Brodmann_area). Brodmann Areas are then listed in the **Tables 2–4** to permit a more specific report of significantly correlated areas in cortex characterized in this experiment. Results presented here survive a statistical correction for multiple comparisons at a false discovery rate (FDR) threshold $p < 0.05$.

Between condition comparisons—sensory processes supporting visual properties during reasoning

First, we predicted that color and BWVC would contribute additional sensory demand during relational reasoning. This was confirmed in our behavioral results demonstrating that RTs increase as a function of complexity within BWVC and Color conditions (**Table 1**). By controlling for the cognitive demand of reasoning within each level of complexity we were able to assess the sensory areas that support the processing of each type of visual property (**Table 2**). A statistical contrast between BWVC and NC trials at 0-complexity shows correlated BOLD signal in bilateral BA 18/19. At 1-complexity level, sensory processing summates in left BA17, bilateral BA18/19, and left BA19. Finally, at 2-complexity, activation is significant in left BA18, right BA19 (bilateral lingual gyrus). Next, the statistical contrast between Color and NC show results at 1-complexity level, with sensory processing contributions from bilateral Brodmann Area 18. Color at the 2-complexity level shows sensory processing contributions from left BA18 and bilateral BA19, classically defined cortical areas of color perception.

Within condition comparisons of relational complexity—influence of visual properties on relational reasoning

Within the Color 2-relational vs. 1-relational contrast, several prefrontal activations survive correction for multiple comparisons at FDR ($p < 0.05$) threshold including: right BA8, left BA6, bilateral BA10. In posterior sensory areas, significance appears in dorsal stream visual areas bilateral BA7, and BA18 in the ventral stream (**Table 3** and **Figure 4**).

To extend our examination of RC results within Color, we performed a functional and structural region of interest (ROI) analysis across different complexity levels in areas found to be significant (**Tables 4**, **5**). A signal intensity analysis for Color 0-, 1-, and 2-relations showed that percent signal changes in BA6, 8, and 10 were significantly higher in 2-RC when compared with 0- and 1-RC (**Figure 5**). Of note, stimulus presentation

Table 2 | Sensory contributions to reasoning—neuroanatomical results for random-effects analysis between BWVC, Color, and NC conditions at 0, 1, 2 complexity.

Regions of activations Anatomical label	BA	Cluster voxel size (uncorrected value)	MNI coordinates			Z-score
			x	y	z	
BLACK-WHITE 2-RELATION > NO-COLOR 2-RELATION						
Occipital						
L Lingual gyrus	18	375	−9	−82	2	4.94*
L Lingual gyrus	18		−24	−76	−9	4.64*
R Lingual gyrus	19		24	−59	−5	4.49*
BLACK-WHITE 1-RELATION > NO-COLOR 1-RELATION						
Occipital						
L Cuneus	17	248	−9	−90	7	5.58*
L Lingual gyrus	18		−6	−76	4	5.49*
R Lingual gyrus	19		21	−67	−4	5.10*
L Lingual gyrus	18	50	−18	−70	−7	4.30*
L Fusiform gyrus	19		−21	−62	−10	4.25*
L Lingual gyrus	18		−33	−74	−9	3.62*
BLACK-WHITE 0-RELATION > NO-COLOR 0-RELATION						
Occipital						
L Lingual gyrus	19	141	−30	−64	−5	5.26*
L Middle occipital gyrus	19	72	−48	−78	9	4.94*
R Lingual gyrus	19	129	21	−70	−4	7.89*
R Fusiform gyrus	19		30	−62	−7	4.72*
L Cuneus	18	34	−9	−87	13	4.09*
R Superior occipital gyrus	19	42	33	−80	23	4.05*
Temporal						
R Middle temporal gyrus	19		45	−78	20	3.92*
COLOR 2-RELATION > NO-COLOR 2-RELATION						
Occipital						
L Lingual gyrus	18	47 (147)	−27	−78	−15	4.69*
	18		−12	−84	−9	4.34*
R Fusiform gyrus	19	(25)	30	−69	−18	3.88
L Fusiform gyrus	19	(17)	−27	−51	−18	3.63
COLOR 1-RELATION > NO-COLOR 1-RELATION						
Occipital						
R Lingual gyrus	18	297 (324)	27	−57	−12	5.98*
	18		30	−69	−12	5.81*
L Lingual gyrus	18	318 (355)	−30	−60	−15	5.30*
L Cuneus	18	39 (49)	−9	−96	18	4.69*
R Cuneus	18	89 (99)	15	−99	21	4.32*
COLOR 0-RELATION > NO-COLOR 0-RELATION						
Frontal						
L Precentral gyrus	4	23	−33	−18	39	4.02
L Middle frontal gyrus	10	10	−36	45	9	358
Cerebellum						
L Posterior lobe		15	−6	−40	−40	3.94

*All regions consist of atleast 7 voxels with an uncorrected P < 0.001; *significance P < 0.05 False Discovery Rate (FDR) correction.*

in our task had a short inter-stimulus interval (ISI), and since RLPFC activations are substantially delayed relative to the onset of each trial (Wright et al., 2008), return toward baseline activation was observed as a negative signal change value. In this context, the trend demonstrates a parametric effect

of increased activity coupled with an increase in complexity level.

Finally, to further examine the pattern of response, Finite input response (FIR) curves were modeled for Color 1-relational and 2-relational conditions in each statistically significant ROI. The

Table 3 | Influence of visual properties on neural systems of relational complexity—neuroanatomical results for the random-effects analysis within Color and BWVC conditions.

Regions of activations	BA	Cluster voxel size	MNI coordinates			Z-score
Anatomical label		(uncorrected value)	x	y	z	
COLOR 2-RELATION > COLOR 1-RELATION						
Frontal						
L Middle frontal gyrus	6	38 (53)	−30	6	60	5.03*
R Medial frontal gyrus	8	33 (53)	6	18	48	4.88*
R Middle frontal gyrus	10	20 (57)	45	54	−3	4.84*
L Middle frontal gyrus	10	(7)	−36	57	18	3.54
Parietal						
L Superior parietal lobule	7	72 (195)	−33	−63	57	4.78*
R Precuneus	7		21	−78	51	3.88*
R Superior parietal lobule	7	38 (90)	33	−63	54	4.19*
L Precuneus	7		−3	−66	54	4.17*
Occipital						
R Inferior occipital gyrus	18	29 (44)	30	−99	−3	5.00*
L Lingual gyrus	18	(19)	−24	−102	−3	3.97
BLACK-WHITE VISUAL CONTRAST 2-RELATION > BLACK-WHITE VISUAL CONTRAST 1-RELATION						
Frontal						
R Middle frontal gyrus	9	(21)	39	13	27	3.81
Parietal						
L Postcentral gyrus	4	(19)	−39	−21	45	4.11
L Postcentral gyrus	2		−45	−27	37	3.75
L Postcentral gyrus	2		−33	−27	40	3.48
R Inferior parietal lobule	40	(10)	33	−53	41	3.56
Occipital						
L Cuneus	18	(75)	−15	−96	10	4.36
L Cuneus	18		−12	−90	18	3.91
L Middle occipital gyrus	19		−24	−95	16	3.46
R Lingual gyrus	19	(74)	27	−76	−4	4.05
R Lingual gyrus	19		33	−67	−4	3.89
R Lingual gyrus	18		15	−82	−4	3.68

*All regions consist of at least 7 voxels with an uncorrected P < 0.001; *significance P < 0.05 False Discovery Rate (FDR) correction.*

Table 4 | Functional ROI analysis for within-group comparison of the Color group contrasting 2-relational vs. 1-relational conditions.

ROI	Hem	Cluster	BA	T	MNI coordinates	Contrast value	Uncorrected p
Middle frontal gyrus	L	38	6	5.59	−30, 6, 60	3.76	0.000002
Medial frontal gyrus	R	33	8	6.12	6, 18, 48	4.27	0
Middle frontal gyrus*	R	20	10	4.54	45, 54, −3	3.99	0.000046
Inferior occipital gyrus	R	29	18	6.02	30, −99, −3	4.49	0
Precuneus	L	12	7	5.12	−3, −66, 54	4.33	0.000006
Superior parietal lobule*	L	72	7	4.5	−33, −63, 54	4.53	0.000004
Superior parietal lobule*	R	38	7	4.58	33, −63, 57	5.09	0.000031

Demonstrates spherical ROIs at the individual peaks of activation clusters which have been masked with the thresholded activation map for that maxima.

hemodynamic response modeled in FIR had similar time course trends in right middle frontal gyrus (BA10), left middle frontal gyrus (BA6), and precuneus (BA7) for each of Color 1- and 2-RC conditions. Also, FIR models in left and right superior parietal lobules (BA 7) and inferior occipital gyrus (BA18) showed a similar trend in their response pattern for Color 2-RC problems.

DISCUSSION

This experiment examined the influence of specific properties of the visual environment (color and BWVC) on neural systems of RC during non-verbal matrix reasoning. Our aim was to better understand how consilient real-world visual perception influences decision-making by dissociating contributions of sensory
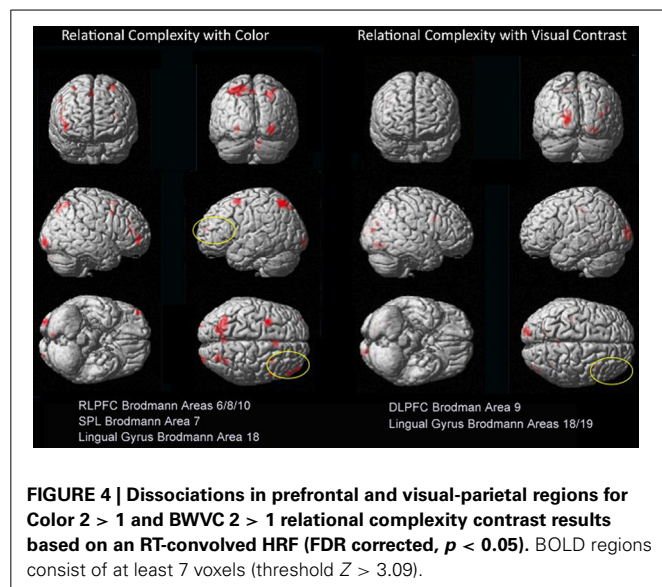
FIGURE 4 | Dissociations in prefrontal and visual-parietal regions for Color 2 > 1 and BWVC 2 > 1 relational complexity contrast results based on an RT-convolved HRF (FDR corrected, $p < 0.05$). BOLD regions consist of at least 7 voxels (threshold $Z > 3.09$).

Table 5 | Structural ROI defined based on anatomical regions identified in previous studies of relational complexity or color perception.

Brodmann area (BA)	Hem	Volume (cm^3)	t	Contrast value	Uncorrected p
BA 6	L	25	1.47	0.63	0.075256
BA 8	L	9	0.11	0.06	0.450611
BA 10	L	14	1.43	0.75	0.918592
BA 7	L	14	2.78	1.33	0.004497
BA 18	L	14	1.72	0.97	0.952954

demand from higher level cognitive processing during relational reasoning. To examine this phenomenon, we used a self-paced, event-related neuroimaging design, incorporating matrix reasoning problems similar to the RPM (Raven, 1938) constructed for 0, 1, and 2 levels of RC with and without color and with BWVC.

This experiment accomplished three aims. First, we were able to dissociate the ways in which color and BWVC contribute additional sensory demand during relational reasoning. When color and BWVC are each compared with the control condition, no color line matrices, neural systems in visual cortex become more localized as problem complexity increases. Black and white visual contrast systems are more salient in the 0-relational condition. Color systems are more salient in the 1-relational condition. This is an artificial comparison because our visual world is comprised of each of these properties. In practical terms, color and visual contrast assist with our perceptual assessment of safety (demarcating boundaries), to our sense of place and capacity to navigate, and to our aesthetic sensibilities for appreciating art, design, architecture, other visual arts and aspects of our daily environments. Importantly, we demonstrate how each property contributes to sensory perception that supports sense-making during problem solving.

Second, elaborating on this discussion, color plays a specific priming role demonstrated by its influence on behavioral RT when an initial change is introduced (1-relation) such that RT significantly varies from both the control and the BWVC condition. This boost in salience is reflected as less RT needed to problem solve at this level.

Lastly, as predicted, this experiment provides direct evidence for the functional connection of the RC system in the RLPFC with ventral and dorsal streams in visual cortex known to support color perception, visual-spatial processing, and navigation. This connection is demonstrated by areas of visual and parietal cortex that are activated with frontal lobe areas that specifically support relational reasoning. As described in the forthcoming paragraphs, we performed an additional region of interest analysis (ROI) to show that the time course and shape of the BOLD response in these sensory areas of the brain (visual and parietal cortices) correspond to BOLD responses assessed in the relational reasoning areas of the brain (frontal cortex) (**Figures 5**, **6**). The BWVC condition is less important during relational reasoning. This is demonstrated on a neural level by areas of visual cortex that are activated with frontal lobe areas that support working memory, processes that are neurally and behaviorally distinct from relational reasoning (Owen et al., 1996; Ruff et al., 2003; Cowan et al., 2012).

Our fMRI results provide evidence that BWVC enlists a "sensory heuristic" during relational reasoning indicated by the multiple areas of the visual cortex listed in **Table 2** that decrease in number as RC increases. Whereas color enlists a "reasoning heuristic" illustrated by the areas of cerebellum and prefrontal cortex that are activated (Rao et al., 1997; Kalbfleisch et al., 2006, 2007) as complexity increases, efficiently utilizing fewer areas of visual cortex than BWVC at higher levels of complexity. These findings demarcate how these two properties of visual perception engage different aspects of sense-making. Taken together, these results demonstrate the collective impact of multiple perceptual systems on reasoning capacities measured in such a way that plausible connections can be made between reasoning competency in the context of real life and the means by which we assess this capacity psychometrically with matrix reasoning tasks.

Consistent with previous studies (Christoff et al., 2001; Kroger et al., 2002), the no color condition in 1-relational vs. 0-relational contrast, showed no significant prefrontal voxel level activation at the uncorrected $P < 0.001$ ($Z > 3.09$) threshold. Within the no color 2-relational vs. 1-relational contrast, activations were localized in BA6, BA8, and BA10 in the RLPFC. Within the BWVC condition, the 2-relational vs.1-relational comparison, activations appear in right BA9, left postcentral gyrus, right BA40, right BA18/19 and left BA18, but are only significant at an uncorrected statistical threshold ($p < 0.001$). This validates previous studies of RC and situates this experiment to extend our knowledge of the role of RC in reasoning and problem solving.

INFLUENCE OF VISUAL PROPERTIES ON SENSORY PROCESSING DURING REASONING

We confirmed our first hypothesis, that sensory properties, represented here as color and BWVC, add cognitive demand to matrix reasoning problems, resulting in a mean stepwise increase in behavioral RTs. One of the roles of the ventral visual stream is to provide visual awareness and meaningful association, "natural
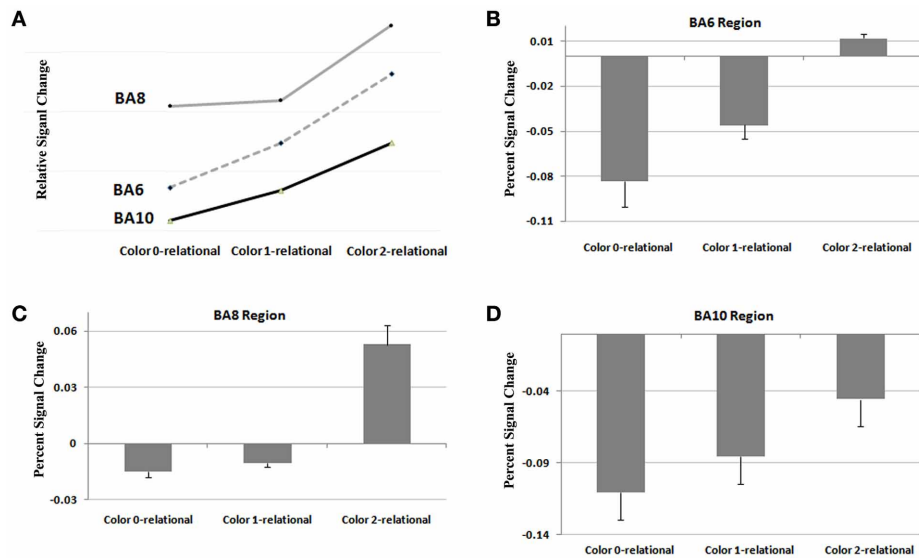
FIGURE 5 | Results from a functional ROI analysis of areas comprising the RLPFC for signal intensity at Color at 0, 1, and 2 levels of relational complexity. (A) Relative signal change in RLPFC across levels of complexity, (B) Percent signal change in Brodmann 6 across levels of complexity, (C) Percent signal change in Brodmann 8 across levels of complexity, (D) Percent signal change in Brodmann 10 across levels of complexity.
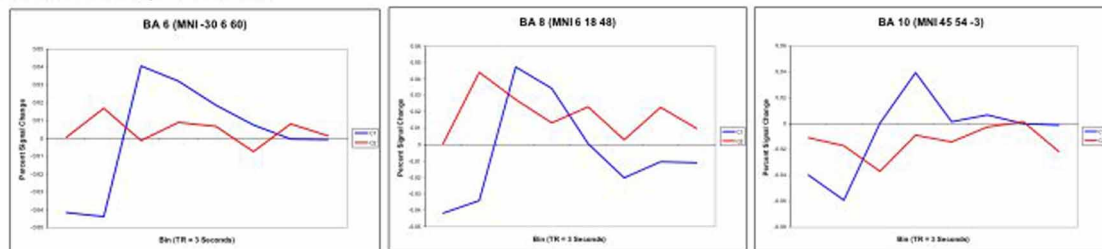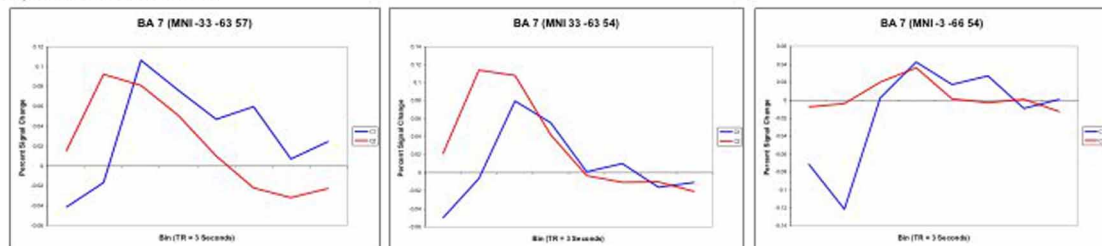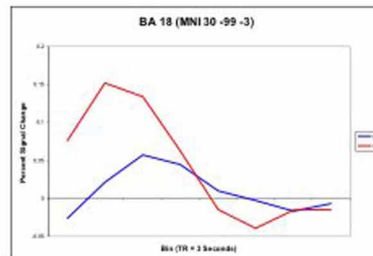

FIGURE 6 | Finite input response (FIR) curves modeling the timecourse of the RT-convolved BOLD response for Color 2-relational (red) > 1-relational contrast (blue) in each statistically significant ROI that links processing in RLPFC with the parietal and visual cortices. ROIs are reported with the associated Brodmann Area and specific Talairach coordinates of the signal maxima from Table 3.

resources" if you will, to the dorsal visual stream to enable goal selection and action (Milner and Goodale, 2006). It helps identify context. Observing the BWVC condition at 1- and 2-levels of complexity shows the visual system becomes more efficient as complexity increases, processing visual information with inputs from a system of less-distributed areas. In contrast with this, color reasoning is only measured at statistically robust levels within 1- and 2-RC. At complexity level 1, dorsal and ventral visual areas are represented, while at complexity level 2, only the left lingual gyrus in the ventral stream is robustly active, a classic color perception area (Zeki and Marini, 1998; Gegenfurtner, 2003; Morita et al., 2004). This suggests that the extra sensory contributions from visual contrast and from color in cortex become more localized as demand increases, transferring salience to other cognitive processes. In our behavioral data, differences between these two visual properties and the control condition, no color line matrices, are statistically significant. This confirms our first hypothesis that input from the environment contributes additional sensory demand at a basic level in appropriate ways parsimonious with perceiving the visual world. On the surface this is not a novel result. However, to our knowledge, this is the first study to extend those findings into an ecologically valid model of decision-making.

THE PARADOXICAL EFFECT OF COLOR ON BEHAVIORAL PERFORMANCE

Unexpectedly, color had a lesser impact on RT as problem complexity increased within the color condition. One possible explanation for this paradoxical effect lies in the fact that color assists with object perception and has a role in scene segmentation and visual memory (Tanaka et al., 2001; Gegenfurtner, 2003; Werner and Chalupa, 2003; Peelen et al., 2009). Thus, color decreases cognitive demand by alerting the brain to salient properties of the visual environment. The behavioral result that RT decreased with the addition of color on the 1-relation trials (**Figure 3**) suggests that color facilitates associative processing by boosting salience to support cognitive performance. In fact, experiments manipulating perceptual demand have shown that response competition effects are eliminated when perceptual demand is at its highest during implicit (Rees et al., 1997; O'Connor et al., 2002; Yi et al., 2004) and explicit changes in visual awareness (Lavie, 2006). This interpretation may also be supported by emerging evidence that general intelligence (IQ) can be predicted by sensory integration and how well someone suppresses interference from visual motion (Melnick et al., 2013).

The priming effect of color on salience addresses the question of how neural systems of RC converge with sensory visual properties to support reasoning and problem solving. When each property is examined within RC (2-relation vs. 1-relation), we demonstrate a double-dissociation between the areas of the prefrontal and visual-parietal cortices for color and BWVC (**Table 3**, **Figure 4**). During color RC, processing from RLPFC works in concert with areas from dorsal and ventral visual streams. The left lingual gyrus in the ventral stream is a classic color perception area. In addition, activity from parietal areas in BA7 (cuneus and superior parietal lobule) in the dorsal visual stream that support RC performance during color conditions is accounted for theoretically and experimentally as the ventral stream perceives objects

and the dorsal stream orients to location (Ungerleider et al., 1998).

The neural correlates that accompany increases in RT suggest that color is a visual property that contributes to cognitive demand in RC. The between condition contrast, color vs. no color, illustrated that the addition of color to RC trials requires additional processing from parietal and ventral occipital areas to process visual information. This is important in light of the evidence that perception of context is engaged early in decision-making and relies on the dorsal stream as a primary pathway for information transfer between the visual and frontal cortices (Kveraga et al., 2007, 2011). As a control condition for color, the BWVC condition demonstrates that color has an additional effect on cognitive processing beyond the presence of a degree of change between no color line matrices and those with BWVC.

THE IMPACT OF COLOR ON RELATIONAL COMPLEXITY

An additional question motivating the experiment was how the actual measure of RC (contrasting 2- to 1-relational performance) would be influenced by color? We assessed this by examining the Color 2 vs. Color 1 within relational contrast. Our results provide evidence of the recruitment of systems beyond those in the prefrontal cortex that appear necessary for color relational reasoning, extending the known system in RLPFC to include relevant superior parietal and inferior occipital areas (**Table 3** and **Figure 4**). The neural systems supporting color RC are comprised of functional areas underlying different components of our task, including a suite of areas in middle frontal gyrus (left BA6, right BA8, and bilateral BA10 biased toward the right hemisphere), right BA18, and bilateral BA7. Coordinates of the left middle frontal gyrus in our experiment are almost identical to the ones reported by Christoff et al. (2001), though we report a bilateral signal in BA10 biased in strength to the right hemisphere. Bunge et al. (2009) report findings to illustrate the differential roles of the left and right hemispheres of the RLPFC. Specifically, the left hemisphere is the primary source of the integration of relations, while the right hemisphere attends to the set maintenance of the complexity. While we report bilateral activation of RLPFC during color RC, only the right hemisphere survives statistical correction. Collectively, the involvement of left BA6 in spatial working memory (Glahn et al., 2002; Wager and Smith, 2003; Tanaka et al., 2005), the role of BA8 in managing uncertainty and approximation (Volz et al., 2005), and BA10's role in RC (Christoff et al., 2001; Kroger et al., 2002), support the suggestion that these areas appear to function in a set capacity, to help the brain maintain salience with overall context and state while more task specific processes occur in the opposite hemisphere. Undoubtedly, higher cortical processes interact with perceptual neurological systems and share their cognitive resources (Petrides, 2005; Simmons et al., 2007; Mahon and Caramazza, 2009; Whitney, 2009). It has been suggested that the occipito-parietal lobe is sensitive to the complexity of relational information (Phillips and Niki, 2006; Wendelken et al., 2008b), and that parietal neurons support associative representation and "contribute to a distributed network that supports learned associations during visual stimulation and working memory periods" (Fitzgerald et al., 2011). These areas collectively demonstrated in our results suggests a parsimonious

outcome for how RC merges with other processes to make visual reasoning possible in everyday life.

Color 2-RC problems in our task recruited bilateral BA7. Activations in BA7 have been previously associated with working memory, setting attention priority, potential movement coding (Shibata and Ioannides, 2001; Molenberghs et al., 2007) and visual-spatial imagery processes (Ruff et al., 2003). The fit curves from our ROI analysis demonstrate that the engagement of the superior parietal lobule (BA7) was modulated by task complexity and also paralleled the trend of the hemodynamic response observed in the middle frontal areas (**Figure 6**). This correlate suggests that parietal engagement in color RC supports activity in these prefrontal areas during RC. In addition to its role in spatial shifting, Wendelken et al. (2008a) submit that BA7 is sensitive to relational structure as well as grouping and serial order combinations. This is particularly important because they make their case for the role of BA7 as a flexible and general support structure for spatial information.

Our color RC task engages aspects of two systems that have been historically distinct in their roles, ventral and dorsal visual pathways (Mishkin et al., 1983; Kravitz et al., 2011) and parietal pathways designated for perception and action (Milner and Goodale, 2006). The color RC system captured here points to the type of top–down influence from higher-order brain areas that guide goal-directed behavior (Sakai, 2008) and facilitate object recognition when compared to achromatic stimuli (Kveraga et al., 2007). These areas work in concert as the posterior parietal cortex has limited memory capacity on its own to retain rich representations of the visual world (Todd and Marios, 2004).

The summative functional system represented in this data suggests there is a boundary condition delineating color's role in priming (Zago et al., 2005) and dissociates salience at two different levels of visual complexity. On a behavioral level, this enhances the visual target over background objects. The supportive effect of color at the highest level of RC suggests there is a boundary condition present in how the brain utilizes or encodes color perception during higher-level cognition. As our behavioral data indicate and the robust bilateral activations present in the cuneus and lingual gyrus present when color is introduced at 1-RC (**Table 2**) vs. 2-RC, activity in the visual system has pared down to the left lingual gyrus in the absence of competing visual complexity. In this case, it may be perceived as its own object *per se*, imposing cognitive demand that results in a longer RT. The practical outcome of this result provides a general principle for using color to prime or ready the cortex for more complex problem solving, a variable easily manipulated in the design of virtual worlds and gaming environments.

CONCLUSION

Our data point to two plausible mechanisms that can be probed in future experiments. First, prior evidence suggests that color engages perceptual processes much faster than was previously thought (Holmes et al., 2008; Seymour et al., 2009) and takes longer to bind (Bartels and Zeki, 2006), lending an explanation for how it imposes influence on contextual salience. Second, it has also been suggested that activity in V4, the "color" area in visual cortex, extends beyond sensory memory (which diminishes in less than 500 ms) and is a fundamental support for short-term memory bridging between conscious and non-conscious processing (Sligte et al., 2009). Taken together, these results provide a plausible explanation for the means by which color influences sense-making from a constructivist perspective.

Prior to this, the effect of color on the mental representations of relations and the level of visual complexity of a task was unknown. When color is "added" to the environment of our task conditions, perceptual systems in the brain are enlisted to detect it. Further, the facilitation effect we find illustrated behaviorally at 1-relation, shows that when color is present in a moment of reasoning, it is incorporated into and enhances the mental representation of the stimulus (i.e., its navigational significance). This is an important distinction, the distinction between perception of color as a general property in the visual environment and color as an object property of a stimulus in the neuroimaging environment. Early experiments exploring aspects of complexity within several different visual properties determined that features of symmetry and context reduce the psychological perception of complexity (Chipman, 1977), a potential explanation for color's influence on behavior during 1-relational problem solving.

It is worth noting a potential limitation but important feature of our study. We did not vary color as a dimension of RC *per se*. Our choice to use the color blue as a starting point came from the fact that it is a color most people can perceive, including those with color-blindness (Deeb, 2004). Had we introduced other colors into the experiment to vary color as a specific aspect of RC, we would have introduced an attention confound as some colors, such as red and green, are known from an evolutionary standpoint to have greater salience (Gerl and Morris, 2008). Also, blue/yellow color vision phylogenetically preceded red/green color vision and is perceived with black/white (rods) to improve scene and context detection. Introducing red/green color heuristics into the experiment could have confounded our ability to measure the effects of color complexity on rational scene analysis and problem solving. No activations were measured in the frontal cortex in the contrasts Color 1 vs. NC 1 or Color 2 vs. NC 2-RC. This result aligns with a previous report that the frontal cortex is not engaged in selecting color on its own (Rowe et al., 2005).

In total, this experiment yields results that discern rules for how the brain employs different and specific reasoning and sensory heuristics for processing color and visual contrast to show how these features are assimilated during problem solving. By demonstrating this within the context of matrix reasoning, we have preserved the relevance of neuroimaging to inform our understanding of the assessment of human intelligence and to influence the design and optimization of formal and informal physical and virtual learning environments.

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Oscillatory EEG correlates of arithmetic strategies: a training study

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There has been a long tradition of research on mathematics education showing that children and adults use different strategies to solve arithmetic problems. Neurophysiological studies have recently begun to investigate the brain correlates of these strategies. The existing body of data, however, reflect static end points of the learning process and do not provide information on how brain activity changes in response to training or intervention. In this study, we explicitly address this issue by training participants in using fact retrieval strategies. We also investigate whether brain activity related to arithmetic fact learning is domain-specific or whether this generalizes to other learning materials, such as the solution of figural-spatial problems. Twenty adult students were trained on sets of two-digit multiplication problems and figural-spatial problems. After the training, they were presented with the trained and untrained problems while their brain activity was recorded by means of electroencephalography (EEG). In both problem types, the training resulted in accuracies over 90% and significant decreases in solution times. Analyses of the oscillatory EEG data also revealed training effects across both problem types. Specifically, we observed training-related activity increases in the theta band (3–6 Hz) and decreases in the lower alpha band (8–10 Hz), especially over parietooccipital and parietal brain regions. These results provide the first evidence that a short-term fact retrieval training results in significant changes in oscillatory EEG activity. These findings further corroborate the role of the theta band in the retrieval of semantic information from memory and suggest that theta activity is sensitive to fact retrieval not only in mental arithmetic but also in other domains.

Keywords: arithmetic, theta oscillations, alpha oscillations, memory and learning, problem solving, strategy training, EEG, memory retrieval

INTRODUCTION

While mathematical proficiency represents an important goal that one needs to achieve throughout education, many children experience difficulties in picking up these competencies. A pivotal objective of educational psychological science thus deals with the understanding of the (neuro)cognitive processes that underlie this development of mathematics, which provides us with crucial information to devise appropriate learning environments (Kilpatrick et al., 2001). The present study focused on the development of different strategies that are used when solving arithmetic problems. Specifically, we used electroencephalography (EEG) to examine how the neural processes that underlie arithmetic strategies change as a function of training. In this vein, our study adds to a growing body of data showing that the human brain is remarkably plastic and that its structure and function is shaped through education and intervention (e.g., Kelly and Garavan, 2005; Draganski and May, 2008; Zamarian et al., 2009).

There has been a long tradition of research in the fields of mathematics education and cognitive psychology, which revealed that children and adults use different strategies to solve elementary arithmetic problems, such as $6 + 9 =$ or $4 \times 3 =$ (e.g., Siegler, 1988; Lefevre et al., 1996; Siegler et al., 1996; Campbell and Xue, 2001; Geary, 2004). These problems are solved either by directly retrieving the correct answer from long-term memory (retrieval strategy), or by using more time-consuming effortful procedural strategies, such as counting or transforming the problem into smaller sub-problems to arrive at the correct solution (e.g., $7 + 8 = 7 + 3 + 5 = 15$). Children progress throughout development from initially using mainly effortful procedural strategies, such as finger counting, to an increasing reliance on retrieval strategies (Siegler et al., 1996), yet both strategies continue to exist into adulthood. It is important to note that difficulties in this development constitute the hallmark of children with mathematical difficulties, who experience problems in both the acquisition of procedural strategies and arithmetic facts (e.g., Geary, 2004; Berch and Mazzocco, 2007). Against this background, it is important to understand the cognitive as well as neuronal processes that underlie these different strategies and their development.

Neurophysiological studies have recently begun to investigate brain correlates of arithmetic strategy use (for a review, cf. Zamarian et al., 2009), providing a new level of analysis that goes beyond behavioral data and that adds new insights into the cognitive

processes of arithmetic strategy use and its development (cf. De Smedt et al., 2010). In the majority of these studies, strategy use was examined by contrasting the brain responses between problems in which the size of the operands was systematically varied, assuming that different problem sizes would trigger different types of strategies. More specifically, it has been widely established that in skilled adults problems with smaller operands (i.e., sums ≤ 10; small problems) are more frequently solved by means of fact retrieval than problems with larger operands (i.e., sums > 10; large problems), whereas procedural strategies occur more often in large compared to small problems (Lefevre et al., 1996; Campbell and Xue, 2001).

Following this problem size approach, studies with functional magnetic resonance imaging (fMRI) have provided valuable insights into the brain regions that are involved when different strategies are applied. In general, there is increasing evidence that left-hemispheric perisylvian regions, including the angular gyrus, are consistently more active during the solution of small problems, which indicates that these regions support the retrieval of verbally stored arithmetic facts. On the other hand, a bilateral fronto-parietal network covering the intraparietal sulci is typically more engaged during the solution of problems with larger operands, suggesting the involvement of this network in the application of procedural (calculation) strategies (Stanescu-Cosson et al., 2000; Zago et al., 2001; Kong et al., 2005; Grabner et al., 2007a). These findings are complemented by investigations of event-related potentials (ERPs) in the electroencephalogram of the brain's electrical activity, which inform us about the time-course of brain activity during arithmetic problem solving. Several ERP-studies have shown that problem size modulates the amplitude of late ERP components occurring after about 300–400 ms (e.g., Jost et al., 2004a,b; Nunez-Pena et al., 2006; Ku et al., 2010), with a more pronounced negativity over right temporo-parietal cortices for large compared to small problems.

In addition to analyses of the functional topography using fMRI and the time-course of brain activity based on ERPs, there is growing interest into oscillatory EEG activity during problem solving, specifically into strategy-related changes in brain oscillations (i.e., induced EEG activity). These changes are related to the coupling and uncoupling of functional networks in the brain and, thus, provide incremental insights into how task-related neuronal networks are formed and interact with each other (Neuper and Pfurtscheller, 2001; Klimesch et al., 2005; Bastiaansen and Hagoort, 2006). Moreover, in contrast to ERPs whose analysis requires averaging over 50–100 trials, reliable measures of induced EEG activity can be obtained based on only a few trials, which makes it a promising candidate for the development of electrophysiological markers of strategy use (De Smedt et al., 2009; Grabner and De Smedt, 2011). A well-established method to quantify induced EEG activity is event-related synchronization (ERS) and desynchronization (ERD; for a review, cf. Neuper and Klimesch, 2006). The ERS/ERD method calculates the percentage amount of band power increases (ERS) or decreases (ERD) in a particular frequency band from a pre-stimulus reference interval to an activation interval (for a more detailed description of this method, see Pfurtscheller and Lopes Da Silva, 2005). Studies applying the ERS/ERD methodology have accumulated much evidence suggesting differential functional

significance of various frequency bands. Bandpower increases (ERS) in theta activity (about 3–6 Hz) have been associated with memory encoding and retrieval, in general (Klimesch et al., 1997; Burgess and Gruzelier, 2000; Jensen and Tesche, 2002), and with retrieval of lexical-semantic information from long-term memory, in particular (Bastiaansen et al., 2005; Bastiaansen and Hagoort, 2006; Grabner et al., 2007b). Bandpower decreases (ERD) in alpha activity (about 8–13 Hz) have been observed to vary with task difficulty in various cognitive demands (Neubauer et al., 2006; Ku et al., 2010) and thus have been interpreted as general index of invested cognitive resources (Pfurtscheller and Lopes Da Silva, 1999b).

In the domain of mental arithmetic, studies investigating oscillatory EEG activity are rare. Earle et al. (1996) reported higher left-hemispheric theta bandpower when participants solved arithmetic problems compared to inserting an arithmetic sign into an equation, and this increase in bandpower was interpreted to reflect fact retrieval during arithmetic problem solving. Harmony et al. (1999) observed task-related bandpower changes in the theta (increases) and in the alpha band (decreases) during a complex arithmetic task. Theta effects were interpreted to indicate sustained attention, whereas the alpha effect was interpreted as memory retrieval. Micheloyannis et al. (2005) found frontal theta power increases and parietal alpha power decreases during multiplication relative to viewing numbers.

To the best of our knowledge, oscillatory EEG activity related to arithmetic strategy use has only been investigated systematically in two studies. De Smedt et al. (2009) presented adults with small (sums ≤ 10) and large (sums > 10) addition and subtraction problems, which were selected such that the small problems had a large probability to be solved by means of fact retrieval and the large problems had a large probability to be solved with procedural strategies. These authors observed that brain oscillations in the theta and alpha bands were modulated by problem size. In the theta band, solving small compared to large problems was accompanied by higher left-hemispheric ERS. Large problems, in contrast, were associated by bilateral alpha ERD. In both bands, the differences were mainly located in parieto-occipital areas, which may cover those task-related parietal brain regions that have also been observed in fMRI studies (i.e., angular gyrus and intraparietal sulcus). In consideration of the functional significance of the theta and alpha bands, the authors concluded that the pronounced left-hemispheric theta ERS in the small problems reflected the retrieval of arithmetic facts from memory, whereas the strong bilateral alpha ERD in large problems indicated the higher cognitive investment in applying arithmetic procedures.

Most recently, Grabner and De Smedt (2011) conducted an EEG study in which the problem size approach was for the first time complemented by and compared with the information from verbal strategy self-reports. Similar to De Smedt et al. (2009), participants were presented with small and large addition and subtraction problems but they now had to indicate after the solution of each problem which strategy they applied (i.e., fact retrieval vs. application of a procedure). The ERS/ERD data revealed a high general convergence of analyses based on problem size and on strategy reports. Small and self-reported retrieval problems were accompanied by higher left-hemispheric theta ERS, whereas large and self-reported procedural problems were associated by higher bilateral

ERD in the alpha band. In the theta band and the upper range of the alpha band (i.e., 10–13 Hz), the differences between conditions were again particularly pronounced over parieto-occipital cortices. In a second analysis, the authors directly compared both approaches with each other and found that self-reported strategy use was linked to the EEG data even when problem size was held constant, for example when only large problems were analyzed. Concretely, higher theta ERS for large retrieval compared to large procedural problems was found, which was most strongly pronounced in the left hemisphere over frontal to centroparietal areas. In contrast, problem size did not modulate ERS/ERD within problems that were reported to be solved using the same strategy (e.g., when only problems that were indicated to be solved by means of a procedure were analyzed). These findings have not only corroborated the functional role of the theta band in arithmetic fact retrieval but also provided the first neurophysiological evidence for the validity of strategy self-reports.

Taken together, the aforementioned studies suggest that strategy use in solving arithmetic problems is reflected in task-related changes in oscillatory brain activity (in particular, in ERS/ERD) in the theta and alpha bands. However, this body of evidence remains to be correlational and static in nature, because it is based on comparisons of brain activity between task conditions that are associated with certain strategies based on problem size or self-reports. As a result, these data do not provide information on how brain activity changes in response to training or intervention. Such information is, however, very relevant for educational psychologists, as it has the potential to reveal insights on the impact of mathematics education on the functional organization of the brain. Against this background, we aim to extend the existing EEG studies by focusing on the effect of fact training on oscillatory brain activity.

In the current high-resolution EEG study, we provided participants with an intensive 2-day fact retrieval training prior to the EEG test session. This allowed us to experimentally manipulate the transition from procedural strategies to fact retrieval use. On the day following the training, participants' brain activity was recorded while they were solving the trained problems as well as the untrained problems (i.e., problems of a similar difficulty level that they did not receive during the training). In addition, after solving each problem they were asked to report the applied strategy (retrieval, procedural, or other). The comparison of brain responses to trained and untrained problems will reveal

those brain areas that are modulated by fact training. A similar approach has already been used in fMRI research on mental arithmetic, which provided complementary evidence supporting the functional distinction at the brain level between arithmetic fact retrieval and procedural strategies, which are supported by the angular gyrus and intraparietal sulci, respectively (Delazer et al., 2003; Ischebeck et al., 2006; Grabner et al., 2009b).

Participants were trained on 10 complex multiplication (two-digit times one-digit) and 10 figural-spatial problems (determination of number of faces in three-dimensional geometric objects; see **Figure 1**) over 2 days involving a large number of repetitions so that they could easily solve these problems by fact retrieval after completing the training. We selected multiplication problems because these problems are more frequently solved by means of fact retrieval compared to other operations (Campbell and Xue, 2001), and because fMRI training studies have revealed that multiplication facts can be easily acquired even after a short training period – a process that is also reflected in changes in brain activity (Ischebeck et al., 2007). Similar to a previous fMRI training study (Grabner et al., 2009b), we complemented the multiplication problems with a certain type of figural-spatial problems to investigate whether the previously reported changes in theta and alpha activity are specific to arithmetic fact learning or whether they can also be observed in other, non-arithmetical learning tasks in which a particular skill is being automatized. Notably, Grabner et al. (2009b) revealed that the training of both multiplication and figural-spatial problems resulted in similar changes in brain activation, most importantly in activation increases in the angular gyrus.

We hypothesized that the trained problems would be solved faster, more accurately, and more often by (self-reported) retrieval strategies than untrained problems. In line with the presumed functional role of the theta band in fact retrieval, we expected that solving the trained problems would be accompanied by higher theta ERS than solving the untrained problems. This effect was predicted to be particularly pronounced over parieto-occipital regions. Because the untrained problems are more likely to be solved by means of procedural strategies, they should be associated with larger ERD in the alpha band. Similar to Grabner and De Smedt (2011), we distinguished lower and upper alpha frequencies (cf. Klimesch, 1999) and expected a higher topographic differentiation in the upper alpha band. Against the background of the fMRI data reported by Grabner et al. (2009b), we predicted
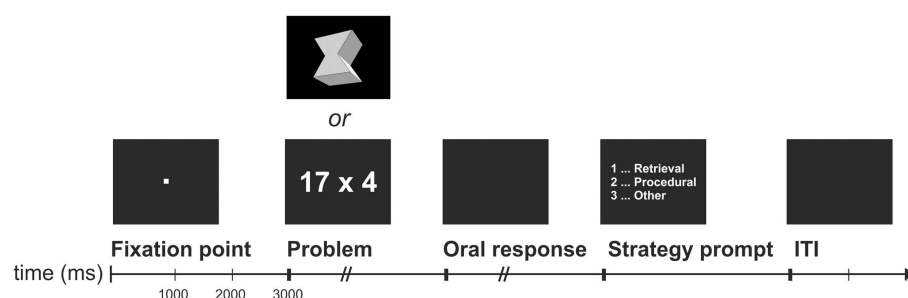

FIGURE 1 | Schematic display of one EEG trial. ITI, inter-trial interval of 2000 ms length.

similar training-related changes in theta and alpha band activity for both, the multiplication and the figural-spatial tasks.

MATERIALS AND METHODS

PARTICIPANTS

Twenty-five adult students were recruited through announcements at the universities in Zurich, Switzerland. All participants were healthy, right-handed, and without known mathematical difficulties. Five participants had to be excluded from the analyses (three due to technical problems during EEG acquisition and two because of a lack of valid EEG trials for analyzing retrieval strategy use). The remaining sample of 20 participants consisted of 9 males and 11 females between 21 and 32 years ($M = 24.30$, SD $= 2.90$). The majority of the participants were psychology students (14/20). The study was approved by the local ethics committee (Swiss Federal Institute of Technology Zurich, Switzerland). All participants gave written informed consent according to the demands of the local ethics committee and were paid for their participation.

MATERIAL

The experimental stimuli comprised 20 multiplication and 20 figural-spatial problems. Similar to previous training studies (Delazer et al., 2003; Ischebeck et al., 2006; Grabner et al., 2009b), the multiplication problems consisted of one operand ranging from 12 to 19 (excluding 15), and one operand ranging from 3 to 8, resulting in products between 42 and 98, excluding solutions divisible by 10. The figural-spatial problems were developed after a figural-spatial subscale of a well-established German intelligence test (Horn, 1983) and were already employed in a previous training study (Grabner et al., 2009b). In each problem, a drawing of a three-dimensional geometric object was presented, requiring the participant to determine the number of object faces as fast and accurately as possible (see **Figure 1**). Each face is defined by salient angles and can be plane, concave, or convex. For example, a cube consists of six faces whereas a sphere has only one face. This type of figural-spatial problems offers several advantages compared to other problems in this domain: It is a valid measure of figural-spatial abilities (Horn, 1962, 1983; Carroll, 1993), it requires numerical responses similar to the multiplication problems (thus, the two problem types only differ in their cognitive demands but not in their response formats), and the solutions to these problems can be also learned as facts (Grabner et al., 2009b). Initially, 40 figural-spatial problems were created. In a pilot study, we presented these 40 problems together with the 20 multiplication problems to 15 participants. On the basis of these data, we selected 20 figural-spatial problems from the initial set that were matched in task difficulty (in terms of response latencies for correctly solved problems) to the multiplication problems.

In both tasks, half of the problems were included in the training sessions, resulting in 10 trained and 10 untrained multiplication and figural-spatial problems, respectively. The trained and untrained problems were matched with respect to problem size (i.e., numerical magnitude of the solution) and task difficulty.

TRAINING PROCEDURE

Participants underwent a 2-day computer training of 10 multiplication and 10 figural-spatial problems. The training software

and a detailed instruction were given to the participants for use on their home computers on a USB stick. Each training session started with a short typing training to familiarize participants with the numerical keypad. In this typing training, random two-digit numbers (40 on the first training day and 20 on the second training day) had to be entered on the numerical keypad as fast as possible. On each training day, the training involved two runs: one run with multiplication and one run with figural-spatial problems (see Grabner et al., 2009b). The order of the runs was randomized. Each run consisted of 15 blocks in which the 10 problems were presented in random order. On the left side of the screen the problem was presented and on the right an empty rectangle appeared into which participants could enter the solution. Participants were instructed to solve the problem as fast and accurately as possible. After giving a solution, positive or negative feedback was provided for 1 s, after which the correct solution was presented for 2 s. The next problem was presented immediately afterwards. To increase training motivation and learning progress, we depicted the number of correctly solved problems and average response latency after each block (i.e., every 10 problems). Before the start of the training on the first day (pre-test) and after completing the training on the second day (post-test), the 10 multiplication and 10 figural-spatial problems were presented once (i.e., one block of multiplication and one block of figural-spatial problems; random order) without feedback in order to quantify the training success. Each training session took about 25–30 min. The training data was automatically saved on the USB stick which was returned at the EEG test session.

EEG TEST PROCEDURE

The EEG test session took place on the day after the last training. EEG recording started with a 3 min rest EEG during which the participant was instructed to open the eyes, close them, or to deliberately blink, roll, and move the eyes. This sequence was required for the automatic reduction of eye movement artifacts (see below). Next, participants were presented with the 20 trained (10 multiplication and 10 figural-spatial problems) as well as the 20 untrained problems (10 multiplication and 10 figural-spatial problems). Every problem was presented four times, resulting in a total number of 160 trials. The trials were divided into two multiplication and two figural-spatial blocks with 40 items each. Within each block, the trained and untrained problems were presented in random order with the constraint that two consecutive trials could not include the same problem or the same solution. The two multiplication and two figural-spatial blocks were presented in alternating sequence. Nine participants of the final sample started with the multiplication block, the other participants with the figural-spatial block.

The temporal sequence of one EEG trial was similar to Grabner and De Smedt (2011) and is depicted in **Figure 1**. Each trial started with the presentation of a fixation point for 3000 ms, followed by a multiplication or figural-spatial problem. The participant was instructed to solve the problem as accurately and quickly as possible. In contrast to the computer training, the participants were required to speak the solution into a voice-activated microphone (voice key) that was connected to the recording computer. The

time period between problem onset and speech onset (as indicated by the voice key) represented the response latency. The oral response was entered into the computer by the experimenter and also digitally recorded for cross-checking after the test session. A timeout of 7000 ms was applied. Immediately following the response, a strategy prompt appeared in the center of the screen asking participants whether they solved the problem by (a) fact retrieval (e.g., remembering the solution or knowing the solution by heart), (b) application of a procedure (arithmetic: e.g., transformation of the problem or counting; figural-spatial: e.g., counting the number of faces), or (c) any other strategy. They indicated the applied strategy by button press after which a blank screen for 2000 ms was presented as inter-trial interval. At the beginning of the EEG test session, participants were carefully instructed on how to report their strategy use following the procedure described by Campbell and Xue (2001) in their study of arithmetic strategy use. A similar instruction was provided for the participants on how to report their strategy use during the figural-spatial task.

EEG DATA ACQUISITION AND ANALYSIS

Electroencephalography was acquired through the BioSemi ActiveTwo system (BioSemi, Amsterdam, Netherlands) from 64 scalp electrodes placed according to the extended 10–20 systems (see **Figure 2**). An electrooculogram (EOG) was recorded from three additional electrodes; two placed horizontally at the outer canthi of both eyes, and one placed above the nasion between in the inner canthi of both eyes. EEG and EOG signals were sampled at 256 Hz and filtered between DC and 128 Hz.

Electroencephalography data analysis was identical to the procedure described in De Smedt et al. (2009) and Grabner and De Smedt (2011). EEG data were first band-pass filtered between 0.5 and 45 Hz to eliminate slow-frequency and power-line contamination artifacts. EOG artifacts were automatically reduced by employing a regression method (Schlogl et al., 2007) based on the resting EEG sequence. The continuous EEG data was then divided into trials of 10 s length (3000 ms before and 7000 ms after problem onset), and all trials were visually inspected for artifacts. The spatial information of the artifact-free EEG data was enhanced by applying a 3D spline surface Laplacian estimation (Babiloni et al., 1998). This procedure has turned out to significantly improve the spatial resolution of EEG potential distributions by reducing head volume conductor effects and by canceling the influence of the electrical reference. ERS/ERD was computed for correctly solved trials only in the theta (3–6 Hz), lower alpha (8–10 Hz), and upper alpha (10–13 Hz) frequency bands (see Klimesch, 1999). To this end, the 10 s trial EEG data was band-pass filtered using a fast Fourier transformation (FFT) based finite impulse response (FIR) method (Oppenheim and Schafer, 1989), yielding a frequency resolution of 0.1 Hz. Afterwards, each amplitude sample of the filtered data was squared by using a moving window (sample-by-sample) of 500 ms length to obtain power values (μV^2). The data from 500 to 2500 ms after trial onset (during the fixation interval) served as the reference interval (R), and the data from problem presentation (at 3000 ms after trial onset) until 125 ms before the oral response as registered by the voice key was used as activation interval (A) for ERS/ERD computation. The last 125 ms (i.e., 32 samples) of the response latency were

FIGURE 2 | Schematic display of EEG electrode positions. For statistical analyses, %ERS/ERD was aggregated over eight areas per hemisphere (electrode positions given exemplarily for the left hemisphere): anteriofrontal (AF; Fp1, AF7, AF3), frontal (F; F7, F5, F3, F1), frontocentral (FC; FC5, FC3, FC1), central (C; C5, C3, C1), centroparietal (CP; CP5, CP3, CP1), parietal (P; P7, P5, P3, P1), parietooccipital (PO; PO7, PO3, O1), and temporal (T; FT7, T7, TP7).

discarded to account for the delay of the voice key trigger signal and to eliminate motor- and speech-related artifacts. For both, R and A intervals, the bandpower values were first averaged over the respective time intervals (horizontal averaging) and then over the trials (vertical averaging), resulting in two values (one for R and one for A) per channel. The amount of ERS/ERD was calculated according to the formula: %ERS/ERD $= [(A - R)/R] \times 100$. Positive values indicate increases (ERS) and negative values indicate decreases (ERD) in band power. It is important to note that the length of the activation intervals (A) varied between individuals and across trials because these trials were defined as the time period from problem onset until 125 ms before the response. This procedure has been repeatedly used in EEG investigations of higher-order cognitive processes (e.g., Grabner et al., 2004; Neubauer et al., 2004; De Smedt et al., 2009; Grabner and De Smedt, 2011) because the activation interval covers the entire time period of problem solving independently of response latency differences between individuals, task conditions, and trials. For statistical analyses, the %ERS/ERD values were topographically aggregated (by using the arithmetic mean) to obtain eight cortical areas per hemisphere (electrode positions given exemplarily for the left hemisphere): anteriofrontal (AF; Fp1, AF7, AF3), frontal (F; F7, F5, F3, F1), frontocentral (FC; FC5, FC3, FC1), central (C; C5, C3, C1), centroparietal (CP; CP5, CP3, CP1), parietal (P; P7, P5, P3, P1); parietooccipital (PO; PO7, PO3, O1), and temporal (T; FT7, T7, TP7; see **Figure 2**).

STATISTICAL ANALYSES

Training data (accuracy, response latency of correct trials) were analyzed using repeated measures ANOVAs including the within-subjects factors Task (multiplication vs. figural-spatial) and Time (pre-test, training session 1, training session 2, post-test). For the behavioral data in the EEG test session, ANOVAs with the within-subjects factors Task and Training (trained vs. untrained problems) were calculated. For EEG data, similar ANOVAs were computed additionally including Hemisphere (left, right) and Area (eight cortical areas as described above) as within-subject factors. ANOVAs on %ERS/ERD data were conducted separately for the three frequency bands (theta, lower alpha, and upper alpha). In all statistical analyses, degrees of freedom were corrected for violations of the sphericity assumption by means of the Huynh–Feldt procedure; the probability of a Type I error was maintained at 0.05. Uncorrected df values together with the corrected p-value and the Huynh–Feldt epsilon (ε) were reported when the sphericity assumption was violated. Eta-squared values were calculated as measures of effect size.

RESULTS

TRAINING DATA

The 2-day training significantly improved the performance in the multiplication and figural-spatial problems (**Figure 3**). On average, accuracies increased from 89.00% in the pre-test to 96.25% in the post-test [main effect of Time, $F(3,57) = 8.13$, $p < 0.01$, $\eta^2 = 0.30$, $\varepsilon = 0.56$]. No interaction with Task was observed, suggesting similar increases in accuracy for both types of problems (see **Figure 3A**). In the response latencies a main effect of Time [$F(3,57) = 38.21$, $p < 0.001$, $\eta^2 = 0.67$, $\varepsilon = 0.39$] emerged, which was additionally moderated by the Task [$F(3,57) = 5.96$, $p < 0.05$, $\eta^2 = 0.24$, $\varepsilon = 0.44$]. As depicted in **Figure 3B**, the response latencies in the figural-spatial problems revealed a steeper training-related decrease than those in the multiplication problems. There were also main effects of Task for accuracies [$F(1,19) = 20.56$, $p < 0.001$, $\eta^2 = 0.52$] and response latencies [$F(1,19) = 26.43$, $p < 0.001$, $\eta^2 = 0.58$], suggesting that solving the figural-spatial

problems was generally easier than solving the multiplication problems (accuracies: 95.43 vs. 90.73%; response latencies: 1.91 vs. 3.03 s; for the figural-spatial and multiplication problems, respectively).
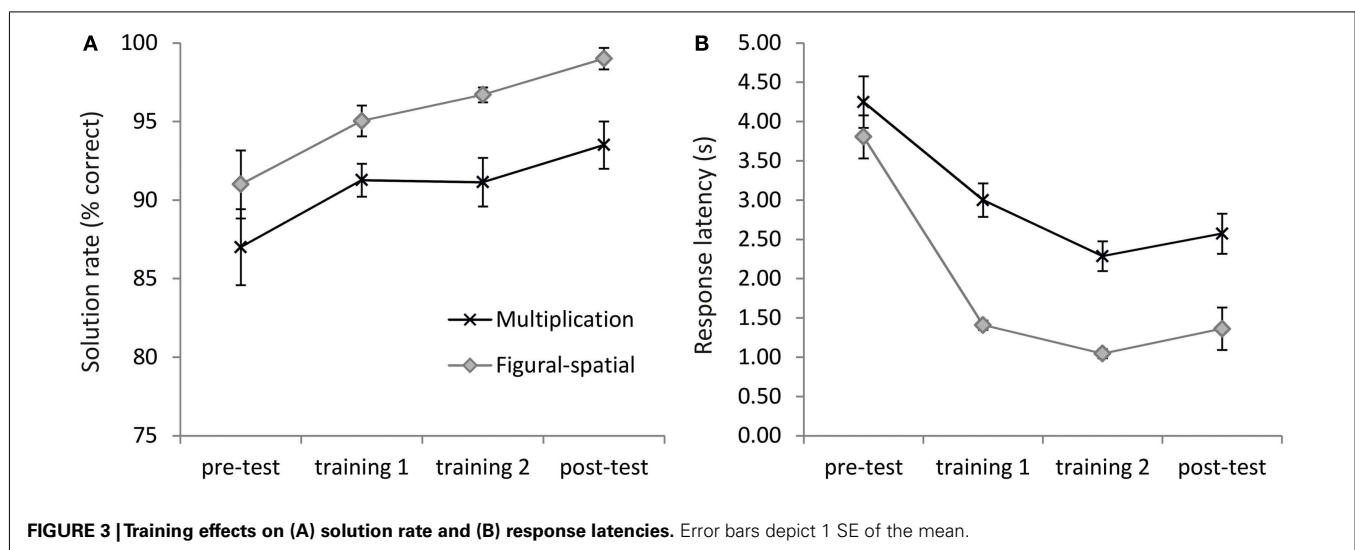
BEHAVIORAL DATA IN THE EEG TEST SESSION

We observed robust and significant effects of Training when comparing trained and untrained problems in both tasks. More specifically, the trained problems were solved more accurately and faster than the untrained problems, as indicated by main effects of Training on both accuracy [93.25 vs. 87.69%; $F(1,19) = 31.49$, $p < 0.001$, $\eta^2 = 0.62$] and response latency [1.47 vs. 2.47 s; $F(1,19) = 235.67$, $p < 0.001$, $\eta^2 = 0.93$]. There were no interactions between Task and Training. Similar to the training data, accuracies were higher (93.94 vs. 87.00%) and response latencies shorter (1.49 vs. 2.45 s) for the figural-spatial compared to the multiplication problems, as indicated by main effects of Task for accuracy [$F(1,19) = 27.16$, $p < 0.001$, $\eta^2 = 0.59$] and response latencies [$F(1,19) = 37.46$, $p < 0.001$, $\eta^2 = 0.66$].

Training also impacted on the self-reported strategy use. Within the correctly solved multiplication problems, 50.42% of the trained compared to 8.57% of the untrained problems were reported to be solved by means of fact retrieval [$t(19) = 8.16$, $p < 0.001$]. Likewise, but even more strongly pronounced, retrieval strategy use was 94.04% and 35.06% on the correctly solved trained and untrained figural-spatial problems, respectively [$t(19) = 22.16$, $p < 0.001$]. Because strategies other than retrieval or procedures were only reported in very few trials (2.96% of the multiplication and 1.68% of the figural-spatial problems), the amount of the procedural strategy use is practically inverse to that of the retrieval strategy use.

EVENT-RELATED (DE-)SYNCHRONIZATION (%ERS/ERD)

In the theta band (**Figure 4**), main effects of Training [$F(1,19) = 19.83$, $p < 0.001$, $\eta^2 = 0.51$] and Task [$F(1,19) = 9.88$, $p < 0.01$, $\eta^2 = 0.34$] were observed, suggesting generally higher theta ERS for trained compared to untrained problems (18.53
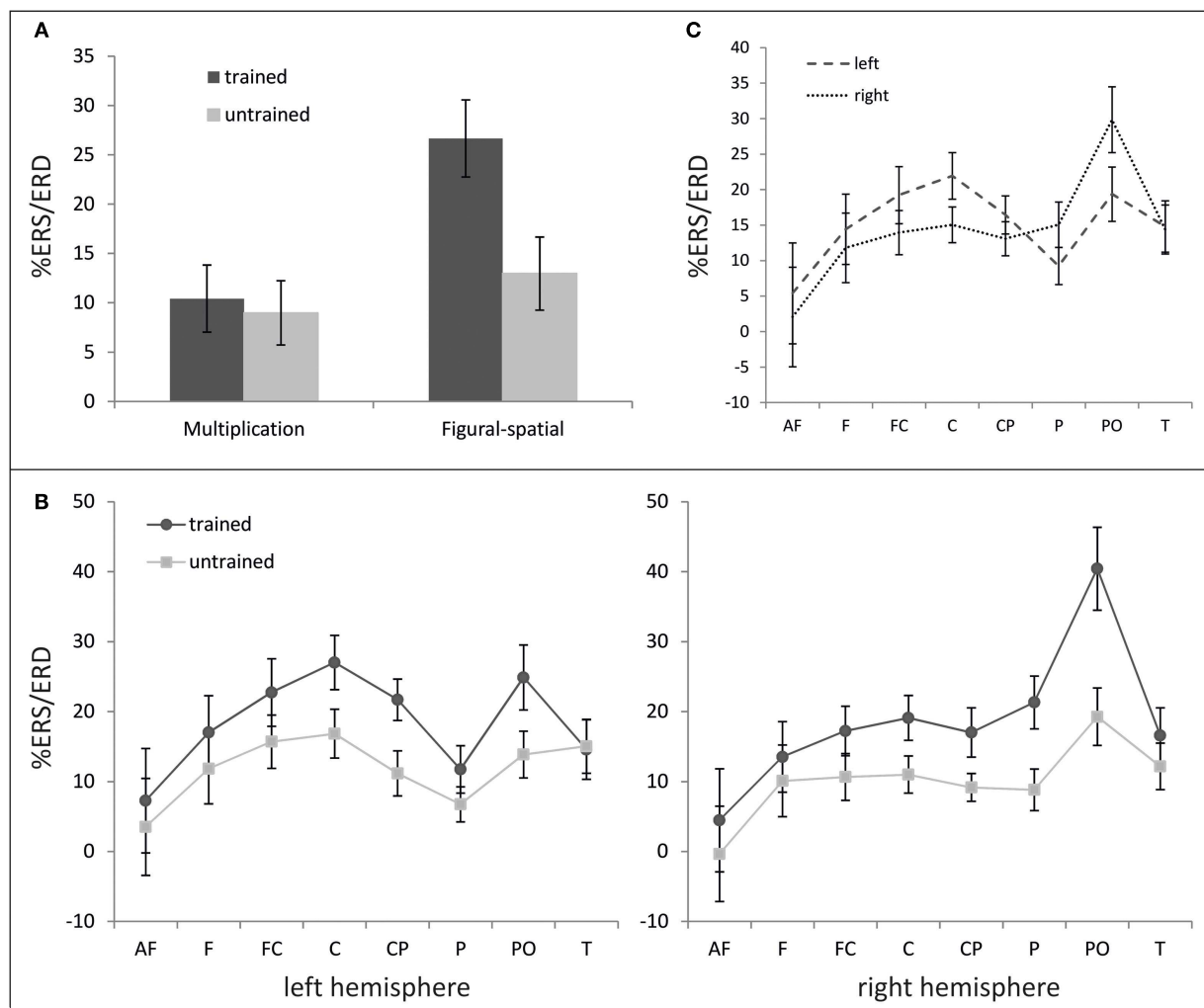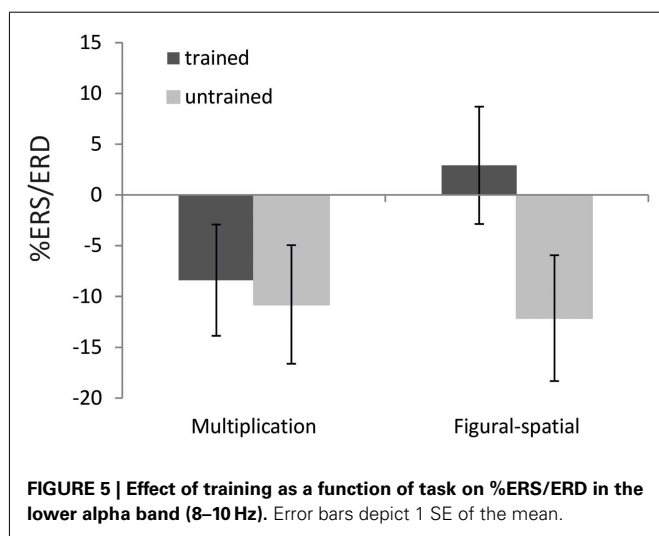

FIGURE 3 | Training effects on (A) solution rate and (B) response latencies. Error bars depict 1 SE of the mean.

FIGURE 4 | %ERS/ERD in the theta band (3–6 Hz). (A) Effect of training as a function of task. **(B)** Topography of training effect. **(C)** Hemispheric differences depending on cortical area. Error bars depict 1 SE of the mean. AF, anteriofrontal; F, frontal; FC, frontocentral; C, central; CP, centroparietal; P, parietal; PO, parietooccipital; T, temporal.

vs. 10.97%) and figural-spatial compared to multiplication problems (19.81 vs. 9.70%). As depicted in **Figure 4A**, the training effect was additionally moderated by Task [Training × Task; $F(1,19) = 14.62$, $p < 0.01$, $\eta^2 = 0.44$], indicating that the difference between trained and untrained problems was larger in the figural-spatial than in the multiplication problems. The training effect also interacted with Area [Training × Area; $F(7,133) = 5.23$, $p < 0.01$, $\eta^2 = 0.22$, $\varepsilon = 0.57$] as well as with Area and Hemisphere [Training × Area × Hemisphere; $F(7,133) = 3.19$, $p < 0.01$, $\eta^2 = 0.14$, $\varepsilon = 0.81$]. These interactions are shown in **Figure 4B** and indicate that the training effect was the strongest over parieto-occipital regions in the right hemisphere. The topographic dominance of the (right) parieto-occipital region was also evident in the main effect of Area [$F(7,133) = 4.73$, $p < 0.05$, $\eta^2 = 0.20$, $\varepsilon = 0.31$] and the interaction between Area and Hemisphere [$F(7,133) = 4.62$, $p < 0.05$, $\eta^2 = 0.20$, $\varepsilon = 0.35$; see **Figure 4C**].

The ANOVA in the lower alpha band also revealed a main effect of Training [$F(1,19) = 9.25$, $p < 0.01$, $\eta^2 = 0.33$], which was further moderated by Task [$F(1,19) = 6.67$, $p < 0.05$, $\eta^2 = 0.26$]. A higher alpha ERD was found in the untrained compared to the trained problems (−11.46 vs. −2.74%), and the training effect was stronger in the figural-spatial compared to the multiplication problems (see **Figure 5**). All other effects were related to the Task. The Task × Hemisphere interaction showed that solving the multiplication problems was accompanied by stronger left (compared) to right-hemispheric ERD, whereas the figural-spatial problems were associated with stronger right than left-hemispheric ERD [$F(1,19) = 13.26$, $p < 0.01$, $\eta^2 = 0.41$]. This was also reflected in the interaction between Task, Hemisphere, and Area [$F(7,133) = 2.65$, $p < 0.05$, $\eta^2 = 0.12$, $\varepsilon = 0.56$], which indicated that solving multiplications particularly induced ERD in the left hemisphere whereas the figural-spatial problems were associated with more ERD in the right hemisphere, particularly in the

right parietal region (see **Figure 6**). The interaction between Task and Area was also significant [$F(7,133) = 4.13$, $p < 0.01$, $\eta^2 = 0.18$, $\varepsilon = 0.46$].

In the upper alpha band, there were no significant effects of Training or Task, apart from a marginally significant interaction between Task and Hemisphere [$F(1,19) = 4.07$, $p = 0.06$, $\eta^2 = 0.18$], which revealed a larger hemispheric ERD difference (in favor of the right hemisphere) in the figural-spatial compared to the multiplication problems. Main effects of Area [$F(7,133) = 4.69$, $p < 0.01$, $\eta^2 = 0.20$, $\varepsilon = 0.48$], Hemisphere [$F(1,19) = 5.58$, $p < 0.05$, $\eta^2 = 0.23$], and the Area × Hemisphere interaction [$F(7,133) = 6.25$, $p < 0.001$, $\eta^2 = 0.25$, $\varepsilon = 0.63$] revealed higher alpha ERD in the right compared to left hemisphere. This was especially pronounced over parieto-occipital regions, where also the largest overall alpha ERD was observed.

FIGURE 5 | Effect of training as a function of task on %ERS/ERD in the lower alpha band (8–10 Hz). Error bars depict 1 SE of the mean.
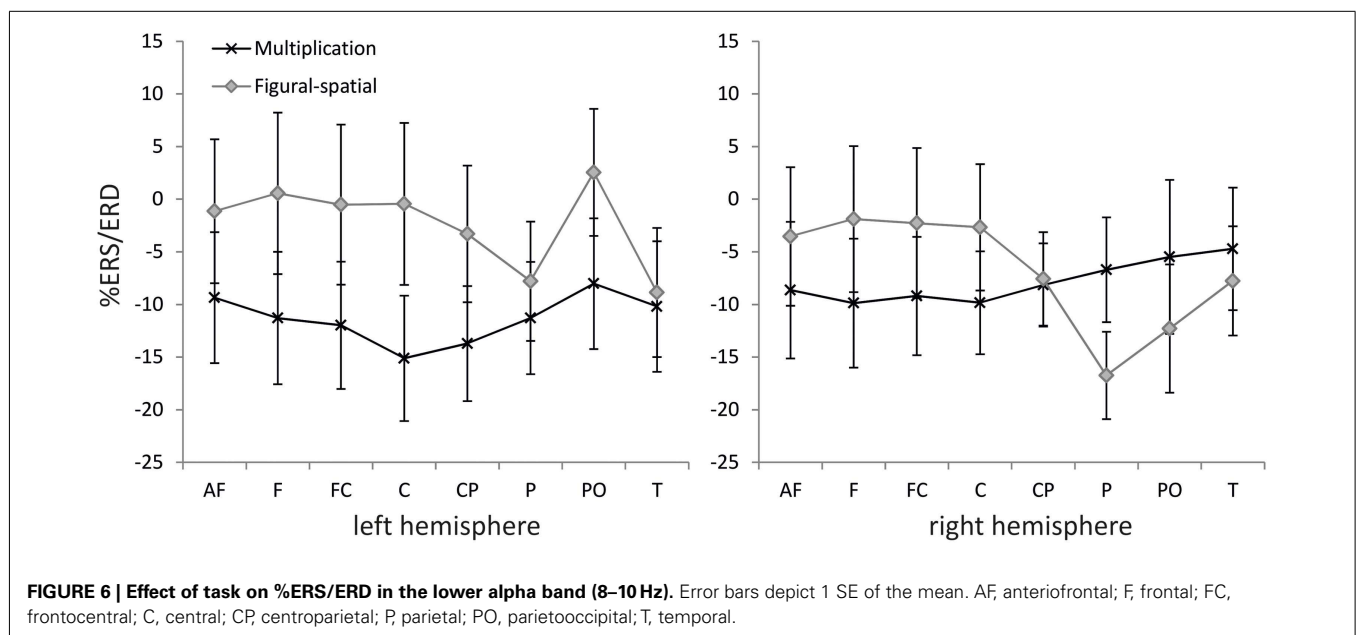
DISCUSSION

In the present high-resolution EEG study we investigated how a 2-day training focusing on fact retrieval changed oscillatory brain activity related to different arithmetic strategies. By administering both, an arithmetic (multiplication) and a non-arithmetic (figural-spatial) task, we also examined how changes in EEG theta and alpha activity were related to specific arithmetic demands. Our results reveal strong training effects on performance, self-reported strategy use, and ERS/ERD in the theta and (lower) alpha band across both arithmetic and figural-spatial tasks. The data also indicate that even a short training can induce significant and specific changes in the brain's electrical activity.

Analysis of the training success and behavioral data in the EEG test session converged to the conclusion that the training worked as expected. Participants became significantly more accurate and faster over the two training days. This was also accompanied by faster and more accurate performance in the trained compared to the untrained problems in the EEG test session. These findings suggest that participants underwent the predicted transition from slower and more effortful procedural to faster and more accurate fact retrieval strategies (Siegler et al., 1996). This is also confirmed by the strategy self-reports that were collected during the EEG test session: Participants indicated that they solved the trained problems more frequently with fact retrieval than the untrained problems. Although the training effect occurred in both tasks, it was more strongly pronounced in the figural-spatial task, as reflected in a steeper training-related decline in response latencies and a higher percentage (more than 90%) of self-reported fact retrieval strategies in the trained problems. This is in line with Grabner et al. (2009b), who administered a similar training over 5 days, and indicates that the figural-spatial facts used in the present study were learned faster than the multiplication facts.

Turning to the oscillatory EEG data, we observed the expected impact of training on theta band activity. More specifically, trained problems were associated with higher theta ERS than untrained

FIGURE 6 | Effect of task on %ERS/ERD in the lower alpha band (8–10 Hz). Error bars depict 1 SE of the mean. AF, anteriofrontal; F, frontal; FC, frontocentral; C, central; CP, centroparietal; P, parietal; PO, parietooccipital; T, temporal.

problems. This finding extends previous results by De Smedt et al. (2009) as well as Grabner and De Smedt (2011) by showing that theta activity not only correlates with different problem sizes and self-reported strategies but also increases as a function of a short-term strategy training focusing on fact retrieval. Consistent with the behavioral data and the strategy self-reports, the training effect in the theta band was more strongly pronounced in the figural-spatial task compared to the multiplication task. This superior training effect in the figural-spatial task explains why the location of the largest topographic training effect was observed over the right parieto-occipital cortex, as the solution of figural-spatial problems is typically associated with stronger right-hemispheric activation (Vogel et al., 2003).

Thus, our data provide further support for a close association between theta activity and the retrieval of semantic information from long-term memory, which has been proposed for both, language processing (Bastiaansen and Hagoort, 2006) and mathematical cognition (De Smedt et al., 2009; Grabner and De Smedt, 2011). Theta activity is assumed to be involved in functionally linking the cortex with the medial temporal lobe (in particular the hippocampus; Bastiaansen and Hagoort, 2003; Klimesch et al., 2005), which is known to play an important role in memory encoding (Gabrieli, 1998) and in retrieval of facts from memory (e.g., Squire et al., 2004) This assumption fits nicely with findings from several recent fMRI studies, showing that parietal cortical areas as well as the medial temporal lobe are involved in mental arithmetic. For example, there is increasing evidence that the angular gyrus mediates the retrieval of arithmetic facts from memory in adults (e.g., Grabner et al., 2009a; Zamarian et al., 2009) and in children (Rosenberg-Lee et al., 2011). Furthermore, recent data in children suggest the involvement of the medial temporal lobe, in particular the hippocampus, in (early stages of) arithmetic fact learning: De Smedt et al. (2011b) found in 10–12-year-olds higher hippocampal activity in small problems and additions, which are likely solved by means of fact retrieval, compared to large problems and subtraction, which are usually solved by means of procedural strategies by children of this age. Against this background, the observed training-related changes in theta activity may reflect the functional interactions between the medial temporal lobe and parietal cortical structures assumed to support arithmetic fact retrieval processes.

Based on previous findings of stronger alpha ERD in large (compared to small) and self-reported procedural (compared to retrieval) strategies (De Smedt et al., 2009; Grabner and De Smedt, 2011), we also predicted training effects in the alpha frequency range, expecting larger alpha ERD in untrained compared to trained problems. Alpha oscillations are assumed to originate from thalamo-cortical and cortico-cortical networks with their amplitude being inversely related to the activated neuronal population, i.e., larger ERD is associated with larger neural activity (Klimesch et al., 2007). We distinguished between a lower and an upper alpha band (below and above 10 Hz, respectively), since both bands have been repeatedly found to differ in terms of localization of the brain activity (Pfurtscheller and Lopes Da Silva, 1999a, 2005; Neuper and Pfurtscheller, 2001): ERD in the lower alpha band typically emerges widespread over the cortex, whereas ERD in the upper alpha band is topographically restricted to task-relevant areas.

In line with our expectations, the untrained (compared to the trained) problems were associated with larger ERD in the lower alpha band. The untrained problems were solved to a larger extent by more effortful procedural strategies and thus required more cognitive investment compared to the trained problems, whose solutions could be often retrieved from memory. This fits with the functional interpretation of alpha band ERD as a general index of invested cognitive resources (Pfurtscheller and Lopes Da Silva, 1999b). The effect of training was also more strongly pronounced in the figural-spatial than in the multiplication task, similar to the training effects observed in the theta band. This suggests that in general, learning of multiplication problems was more resource-demanding than learning figural-spatial problems.

In contrast to our expectations, no effects of training and task were observed in the upper alpha band. Moreover, the expected task-related topographic differentiation was observed in the lower alpha band with the multiplication problems displaying a pronounced left-hemispheric ERD; the figural-spatial problems, on the other hand, were associated with a strong ERD over right parietal regions. Given the lack of comparable training studies on oscillatory EEG activity in the alpha bands, it is difficult to explain the absence of significant training and task effects in the upper alpha band. However, it is noteworthy that Grabner and De Smedt (2011) also reported a higher sensitivity of the lower alpha band to problem size effects. While problem size strongly modulated lower alpha ERD, no such effects were observed in the upper alpha band. Further studies investigating the functional significance and training sensitivity of different alpha frequency bands are needed.

Similar to the fMRI study by Grabner et al. (2009b), we observed training effects on brain activation in both the multiplication and figural-spatial task. Although there was a general training effect on ERS in the theta band and ERD in the lower alpha band, the effect was stronger in the figural-spatial problems, which resembles the behavioral training data. This finding suggests that the training-related changes in theta and alpha bandpower are not specific to arithmetic but reflect a more general domain-independent mechanism in fact learning. In recent fMRI studies, such a domain-independent mechanism has been proposed for the parietal cortex (specifically, in the angular gyrus; Ansari, 2008; Grabner et al., 2011, in press). These studies suggest that the angular gyrus supports the automatic mapping between overlearned problems and their solutions. In other words, whenever a well-trained problem is presented, the solution to this problem is automatically activated and retrieved from memory. This mapping seems to occur within domains, for example in the connection between an arithmetical problem and its numerical solution, as well as across domains, for example a connection between a figural-spatial problem and a numerical solution (i.e., the number of faces, as in the current training study). Although the present EEG data have a poor spatial resolution and do not allow us to draw firm conclusions on the involvement of specific brain regions in cognitive processes, the observation of the strongest training effects over the parietal and parieto-occipital cortex fits nicely with this account.

The present findings indicate that even a short intervention can induce specific changes in the brain's activity. Indeed, the human brain is not a static organ but shows remarkable plasticity in response to experiences in the environment (Jäncke, 2009),

such as instruction. There is a now growing body of studies in the transdisciplinary field of educational neuroscience that is trying to investigate the effects of different learning environments on brain activity. For example, Rosenberg-Lee et al. (2011) demonstrated that 1 year of schooling had tremendous effects on changes in brain activity during the solution of arithmetical problems in primary school children. Similar effects of instruction on changes in brain structure and activity have been observed in the fields of reading (e.g., Keller and Just, 2009) and video game playing (e.g., Voss et al., 2012). These findings are highly relevant for the field of educational psychology as they add to our understanding of how learning takes place and how it can be fostered. However, it needs to be emphasized that the current sample only included adult participants and that the observed findings may not be readily generalized to children. Future research should therefore aim to replicate the current study in a sample of school-aged children.

The present study also illustrates the value added of brain imaging methods to educational research. Indeed, cognitive neuroscience offers a series of tools and methodologies that allow educational psychologists to complement or extend the knowledge they have already accumulated through decades of behavioral research (e.g., Lieberman et al., 2003; De Smedt et al., 2011a, for a discussion). With the advent of non-invasive brain imaging techniques, it is now possible to investigate at the biological level how people learn. The current findings show that the well-known behavioral shift from effortful procedural strategies to fact retrieval

strategies as a function of training is also reflected in specific changes in brain activity. This convergence of findings, obtained by different research methodologies at behavioral and biological levels, provides a more solid empirical ground for our theories on strategy development.

Although the current findings illustrate the effects of training on changes in brain activity, it is important to emphasize that these changes in brain activity may vary as a function of different types of instruction. For example, Delazer et al. (2005) examined the effect of two learning methods, learning by drill (i.e., learn the association between a problem and its answer, as was done in the current study) vs. learning by strategy (i.e., participants learned a sequence of problem solving steps to calculate the solution). They revealed that the drill approach activated the angular gyrus more strongly than the strategy approach. Against this background, future studies should therefore focus more specifically on the effects of different learning environments or instructional approaches on brain activity. Without doubt, such studies will require close collaborations between educational psychologists and cognitive neuroscientists.

ACKNOWLEDGMENTS

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Neuroplasticity-based cognitive and linguistic skills training improves reading and writing skills in college students

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This study reports an evaluation of the effect of computer-based cognitive and linguistic training on college students' reading and writing skills. The computer-based training included a series of increasingly challenging software programs that were designed to strengthen students' foundational cognitive skills (memory, attention span, processing speed, and sequencing) in the context of listening and higher level reading tasks. Twenty-five college students (12 native English language; 13 English Second Language), who demonstrated poor writing skills, participated in the training group. The training group received daily training during the spring semester (11 weeks) with the Fast ForWord Literacy (FFW-L) and upper levels of the Fast ForWord Reading series (Levels 3–5). The comparison group (n = 28) selected from the general college population did not receive training. Both the training and comparison groups attended the same university. All students took the Gates MacGinitie Reading Test (GMRT) and the Oral and Written Language Scales (OWLS) Written Expression Scale at the beginning (Time 1) and end (Time 2) of the spring college semester. Results from this study showed that the training group made a statistically greater improvement from Time 1 to Time 2 in both their reading skills and their writing skills than the comparison group. The group who received training began with statistically lower writing skills before training, but exceeded the writing skills of the comparison group after training.

Keywords: language, writing, reading, neuroplasticity, computer-based instruction, cognitive skills training

INTRODUCTION

While reading instruction is the focus of early literacy skills, as students move into the high school and college years there is increasing focus on writing. By the time U.S. students reach high school it is assumed that they have already learned to spell words and use punctuation in standard ways and that the words and syntax they use in their writing comply with the rules of Standard Edited American English (SEAE) grammar (National Commission on Writing, 2003). Despite the importance for students to become proficient in SEAE writing skills, the National Assessment of Educational Progress' (NAEP) most recent writing assessment showed that only 27% of U.S. students in grade 12 performed at or above the proficient level (National Center for Education Statistics, 2012). Because of the increasing importance of writing for success in college, assessment of proficiency in written SEAE now comprises one-third of the Scholastic Aptitude Test (SAT®; College Board, 2012a). Nearly all 4-year college and universities in the U.S. (including test-optional institutions) use students' SAT scores as a measure of college readiness as well as an indicator of likely college success from students of all backgrounds. The SAT provides subject-level readiness indicators for both Critical Reading and Writing measures. The college enrollment rate of 2011 U.S. high school graduates was 72.35% for young women and 64.6% for young men

(U.S. Department of Labor, Bureau of Labor Statistics, 2012). With such a high number of students enrolled in college one would assume reading and writing scores to be high for this population of students, as college places such heavy demands on both reading and writing. Unfortunately, less than half of 2012 college bound seniors met the SAT College and Career Readiness Benchmark for Critical Reading and Writing: 49% of students met the critical reading benchmark, 51% did not; and 45% of students met the writing benchmark, 55% did not (College Board, 2012b). As the majority of 12th grade students continue to fail to reach proficiency in writing skills many colleges are increasingly faced with providing developmental writing instruction to their students. This may be especially important to those colleges that have a high proportion of students with English as a second language (ESL) and underrepresented minority students.

These data clearly point to the need for more research on the efficacy of writing instruction and intervention strategies for college students who are continuing to struggle with writing. Specifically, there is a need for a better understanding of the foundational cognitive, linguistic, and reading skills important for proficient writing as well as the development of scientifically validated methods and intervention strategies for improving writing at the college level. At the college level, it is also important to develop methods that can be standardized, scaled with efficiency for individualized

use, and demonstrated to generalize broadly to writing in a variety of contexts. Recently, there has been a growing focus on the development of neurocognitive approaches; particularly those based on neuroplasticity research, for improving language and literacy skills (Kujala et al., 2001; Habib et al., 2002; Song et al., 2012). The purpose of the present study was to assess the impact of computer-based cognitive, language, and literacy skills training on the reading and writing skills of college students with demonstrated writing deficiencies. In this study, we address whether intervention strategies derived from physiological and cognitive neuroplasticity research may provide a novel approach for addressing the needs of twenty-first century college students who continue to struggle with writing.

THE LANGUAGE TO LITERACY CONTINUUM

It is our premise that if we want to create more effective instructional and intervention methods for assisting struggling learners, it is important to better understand the causes and determinants of individual differences in the development of higher cognitive skills such as writing. Put simply, we need a better understanding of the foundational neurocognitive, and linguistic skills on which proficient writing depends from a developmental perspective. Graham and Perin (2007) explain that reading and writing are complementary skills that run a roughly parallel course with language. Writing is putting words on paper. Words come from what students hear, speak, and read.

Spoken language is the foundation of written language. In order to break the code for proficient reading, which is linked to proficiency in writing, students must become phonemically aware that words can be broken down into smaller units of sound (phonemes) and that it is these sounds that the letters represent (Lyon, 1995; Castles and Coltheart, 2004). In their earliest reading and writing experiences, students are instructed to listen for the relationships of sounds to letters, which contributes to their phonemic awareness and knowledge of phonics. In addition to the large body of research showing that explicit training in phonemic awareness improves reading (see National Reading Panel, 2000, for review), explicit phonemic awareness training also has been shown to improve writing both in typically developing and at risk students. In a study with typically developing students, Eldredge and Baird (1996) found that students increased their ability to write when a structured phonics program was used as compared to a holistic or whole language approach. The analysis of student's writing revealed that those who received a structured phonics program as compared to those receiving holistic instruction wrote using more words ($p < 0.002$), different words ($p < 0.002$), difficult words ($p < 0.03$), and composition units ($p < 0.002$). In addition, the students in the structured phonics group also surpassed those in the holistic group on the number of words spelled correctly ($p < 0.026$) in written compositions. Finally, the study showed that the overall quality of the written compositions by the structured phonics group were significantly higher than the students in the holistic group with an effect size equivalent to a 49 percentile point difference in performance on this variable. While studies such as this one have typically focused on beginning writers, it is important to note that studies with struggling readers have shown that phonemic deficits continue to occur even in

college students with a history of reading impairments (Gallagher et al., 1996; Wilson and Lesaux, 2001; Cirino et al., 2005; Callens et al., 2012).

In addition to phonemic awareness, reading and writing also depend on other foundational language abilities including semantics, morphology, and syntax (Byrne, 1981; Joanisse et al., 2000; Catts et al., 2002; Carroll and Snowling, 2004). As students progress in reading into the middle school years, morphological awareness plays an increasingly important role in literacy development (Singson et al., 2000). There is a systematic progression of grammatical morpheme acquisition which includes present progressives (-ing), plurals, irregular past forms, possessives, articles, regular past tense verbs, third person singular, simple present tense, and *be* verbs (Lightbown and Spada, 2002). Not only is literacy success dependent on adequate acquisition of these morphological structures, but also on a student's correct application of syntactical rules, for example, in English, the proper temporal order of words within phrases and larger units–e.g., adjectives before nouns. The connection between speaking, reading, and writing is an ongoing cycle with speaking, reading, and writing supporting one another. As they write, most individuals mimic the oral language they hear internally (Carrow-Woolfolk, 1996). While oral expression generally develops without the need for explicit instruction, written communication requires much more deliberate effort and intensive practice to learn to communicate ideas effectively and accurately. When listening or reading, the student passively experiences language structures. Writing, on the other hand, requires students to actively focus on language structures and written conventions in order to learn to reproduce them in written form.

PERCEPTUAL AND COGNITIVE PREREQUISITES FOR LITERACY

There is a large body of research demonstrating a link between individual differences in foundational perceptual and cognitive skills and individual differences in language and reading development and disorders (Farmer and Klein, 1995; Kraus et al., 1996; Stein and Talcott, 1999; Habib, 2000; Wright et al., 2000; Tallal, 2004). Similarly, foundational cognitive skills (memory, attention, processing speed, and sequencing) have also been posited to underlie individual differences in writing. Berninger and Winn (2006) proposed the "not-so-simple-view" of writing. This model asserts that an individual's level of writing competence relies on the efficiency of the writer's cognitive abilities. Multiple areas of the brain must work together to produce writing that conforms to the rules of SEAE. Sentence generation involves consciously reflecting on and manipulating knowledge which needs to be retrieved rapidly from long-term memory or actively maintaining it in short-term working memory with some level of automaticity and with disregard to irrelevant information. Writing consumes the writer's full attention as the writer thinks about what to say and applies correct spelling and syntactical rules to what is written. As the writer fixates on each word in a sentence, all preceding words in that sentence must be maintained in working memory while simultaneously selecting new words in their correct sequence to form correct sentences and paragraphs that convey the intended thoughts.

To write using SEAE, students must remember what they want to write, pay attention to the way they write it (correct spelling, capitalization, and punctuation), and construct what they want to write so that it appears on paper in a logical sequential order using correct vocabulary, morphology, and syntax. Understanding the developmental progression of language skills, coupled with the increasing role of foundational cognitive skills as students attempt more advanced writing seems particularly important in the design of instructional methods to improve writing. Given the strong relationship between basic perceptual, cognitive, spoken, and written language skills, coupled with evidence that early patterns of deficits in struggling students continue to be evident (but are rarely addressed) in older students, we hypothesized that structured methods that explicitly focus on improving basic perceptual and cognitive skills in the context of increasingly challenging language and reading comprehension would result in improvements in reading and writing skills in college students who continue to struggle with writing.

USING NEUROPLASTICITY-BASED TRAINING PROGRAMS TO ENHANCE FOUNDATIONAL PERCEPTUAL, COGNITIVE, AND LINGUISTIC SKILLS

Tallal et al. (1996) and Merzenich et al. (1996) were the first to develop training programs for students with language-based learning deficits that explicitly focused on improving underlying perceptual and cognitive skills in the context of language. Their methods were based on neuroplasticity research in animals that showed that the functional organization of the brain at the cellular level could be changed and behaviors improved by intensive behavioral training (Recanzone et al., 1993). Several training principles were found in these animal studies to be necessary for driving neuroplastic changes in the brain, both at the physiological and behavioral level. These include intensity and frequency of trials, focused attention to a task, individually adaptive (easy to hard) trials, and timely rewards and correction of errors to reinforce learning and maintain motivation.

In order to evaluate whether neuroplasticity-based training could be used to improve language skills in children, Tallal et al. (1996) and Merzenich et al. (1996) developed a series of neuroplasticity-based listening training exercises disguised as computer video games. The exercises were broadly designed to drive neuroplastic changes in attention, processing speed, sequencing, and memory within the context of training language skills from the phonological to the grammatical level. In their first study, they evaluated the efficacy of this approach with children with specific language learning impairments (LLI). Children were quasi-randomly assigned to two matched groups. The language impaired children in both the experimental and control group received the same intensive speech and language intervention over a 4-week training period. However, the experimental group received the training with speech that had been acoustically modified to increase the amplitude and duration of the fastest changing (3–30 Hz) components within syllables and words, while the control group received the training with regular (not modified) speech. In addition, the experimental group played a video game that was designed to individually adapt to increase their rate of auditory processing, while the control group played a visual video game for the same period of time that did not vary the rate of

stimulus presentation. Results showed that neuroplasticity-based training could significantly improve basic auditory processing speed thresholds (Merzenich et al., 1996). Furthermore, while both groups improved in language abilities after the intensive listening training program, the improvements in language abilities were significantly greater for the experimental group (Tallal et.al, 1996). This series of linguistic exercises and video games formed the basis for the Fast ForWord®series of language and reading programs (www.scientificlearning.com).

There are several studies with mixed results that have focused on the effectiveness of the original Fast ForWord Language product for children with specific language impairment or dyslexia (Temple et al., 2003; Troia and Whitney, 2003; Cohen et al., 2005; Gaab et al., 2007; Gillam et al., 2008; Given et al., 2008; Stevens et al., 2008) or rehabilitation of cognitive skills in elderly adults (Szelag and Skolimowska, 2012). The NIH-randomized control trial is the most recent and comprehensive of these studies (Gillam et al., 2008). In this study, 216 children between the ages of 6 and 9 years with language impairments were randomly assigned to one of four conditions: (a) Fast ForWord Language, (b) academic enrichment, (c) computer-assisted language intervention, or (d) individualized language intervention provided by a speech-language pathologist (SLP). All children received 1 h and 40 min of treatment, 5 days per week for 6 weeks. Language and auditory processing measures were administered to the children by blinded examiners before treatment, immediately after treatment, 3 months after treatment, and 6 months after treatment. Gillam et al. (2008) found that children who interacted with computers during their intervention time using Fast ForWord-Language or computer-assisted language intervention (CALI), fared as well as children who received one-to-one individual language intervention with a certified SLP or academic enrichment, all of whom made highly significant improvements on standardized language measures. Furthermore, at the immediate post-test, as well as the 3- and 6-month follow-up testing, participants who were trained with the two computerized instructional programs (Fast ForWord-Language or CALI) that focused primarily on auditory discrimination of sounds, syllables, and words, yielded better phonological awareness results than the computerized treatment that focused on general academic skills or the clinician-directed language treatment. Gillam et al. (2008) concluded that all conditions examined in this study yielded highly significant improvements in language, indicating that intensity of intervention may be the driving factor across conditions. However, they also pointed out that when comparing interventions one should consider that the cost and time investment of the SLP is greater than that of the computerized interventions that were delivered to groups of children.

All of the previously published studies have evaluated the efficacy of the original Fast ForWord-Language products in younger students. Over the years, a much broader series of more advanced exercises have been developed for middle and high school students. Fast ForWord Literacy (FFW-L) and Fast ForWord Reading (FFW-R Levels 3–5) software engage more advanced students in a series of listening, language, and reading exercises designed to build higher-level cognitive and language-based literacy skills. As students progress through the exercises of FFW-L and the FFW-R series, the demands on working memory, attention span,

processing speed, and sequencing are continually increased within the context of increasingly complex linguistic material. To our knowledge, no previously published study has focused on college students or assessed the efficacy of a combination of the FFW-L and higher-level Reading (Levels 3–5) products in improving reading and writing. The present study explored the following main research question: does the Fast ForWord program, aimed at improving basic through advanced cognitive, language, and reading skills, impact college students' reading and/or writing skills? Specifically, this study evaluated the effectiveness of the FFW-L and FFW-Reading exercises in improving reading and SEAE writing skills in college students with poor writing skills.

MATERIALS AND METHODS

RESEARCH DESIGN

This study used a quasi-experimental research design with two groups; below average and good writers. The intent of the experiment was to determine whether providing intensive cognitive, language, and reading training to college students with below average writing skills would generalize to improved writing abilities. In a quasi-experimental research design subjects are not necessarily equal on variables of interest (in this study writing and reading skills) and are not randomized across treatment and control groups.

PARTICIPANTS

The participants in this study were 53 college students enrolled in an urban public university located in northern New Jersey. Approximately 6,000 undergraduate and 4,000 graduate students attend the university. The university has maintained a longstanding commitment to recruiting and supporting ethnic minorities from the surrounding community. Two populations of undergraduate students with historically lower literacy abilities were invited to participate in this study's training group. The first population consisted of students enrolled in a developmental writing course during the 2010 fall semester. If students do not meet the required competencies for enrolling in Composition 101, they are required to pass non-credit developmental writing coursework before they are allowed to enroll in the required Composition classes. The second population of students invited to participate in the training group consisted of students enrolled in the Louis Stokes Alliance for Minority Participation (LSAMP) program. The LSAMP program is aimed at increasing the quality and quantity of underrepresented minority students successfully completing a science, technology, engineering, or mathematics (STEM) baccalaureate degree. Students from the general population of college students at the same University were recruited to participate in the comparison group. All of the students who volunteered were accepted into the study and signed a formal letter of consent. This study was reviewed and approved by the university's Institutional Review Board.

The training group included 25 students, 17 females and 8 males with a mean age of 20.08 years ($\pm$3.57). The comparison group included 28 students, 16 females and 12 males with a mean age of 19.39 years ($\pm$1.37). Gender ratio was similar across groups ($\chi^2 = 0.66$, df $= 1$, $p < 0.416$). ESL distribution was significantly different between the two groups ($\chi^2 = 5.37$, df $= 1$, $p < 0.021$);

the training group consisted of 13 ESL and 12 non-ESL students while the comparison group had 6 ESL and 22 non-ESL students.

COMPUTER-BASED COGNITIVE AND LITERACY SKILLS TRAINING TASKS

The computer-based cognitive and literacy skills training used in this study was FFW-L (Scientific Learning Corporation, 2006) followed by Fast ForWord Reading, Levels 3–5 (FFW-R3, R4, R5; Scientific Learning Corporation, 2011). The training was designed specifically for secondary students with a focus on increasingly demanding cognitive, listening, and reading skills. The exercises individually adapted to increasingly challenge student's memory, attention, processing speed, and sequencing within the context of increasingly demanding spoken and written stimuli. The training provided students with (a) an orienting button that allowed the student to control when each trial was presented (b) frequent stimuli that required sustained attention and a response on each trial, (c) trials that adapted to each student's responses, mouse-click-by-mouse-click, moving from easy to harder trials, and (d) timely feedback, correction of errors, and rewards after each correct response. Exercises in both the literacy and reading series trainings made use of modeled grammatically correct language, repetition of content, instant feedback, individualized instruction, combined auditory and visual stimulation, and concentrated and continuous practice to enhance and automatize listening and literacy skills, all of which are critical components for improving writing. The overarching goal of the series of exercises was to progressively drive more efficient and consistent neural processing as well as to improve performance in the linguistic domains of phonology, semantics, morphology, and syntax within both spoken and written English. However, no explicit practice with writing *per se* was included in the training. Example screen shots and a brief explanation of each of the training exercises used in this study are provided in Supplementary Material.

Language/listening training

Students began with a language/listening training program (FFW-L) that included a series of six training exercises each designed to build auditory perceptual, cognitive, and linguistic skills important for spoken language comprehension. Exercises in this program aimed to help students increase their focused attention and working memory span for auditory/spoken information and strengthen listening comprehension by having students work with auditory sequences, spoken phonemes, morphemes, words, sentences, paragraphs, and full stories. Exercises focused on the use of grammar in sentence context and systematically trained all of the rules of English grammar.

Reading training

Once students completed the language/listening program they progressed to the reading training programs (FFW-R3, R4, & R5). These exercises used a similar format and specifically built upon the cognitive and language skills developed in the first program, but in this case with a focus on written language. These exercises progressed at each student's own pace from a simple focus on letter-sound correspondences, to building an understanding of grammatical morphology, training in writing conventions (i.e., spelling, punctuation, and capitalization), and sentence

and paragraph construction. As students progressed, the exercises required increasing use of executive functions within the context of increasingly challenging linguistic contexts.

Implementation of training

Students in the training group trained 50 min per day, 4–5 days per week for 11 weeks in a computer lab on campus. Students used the software series for 32–50 days ($M = 42$; SD = 5.4). Each training exercise had a set amount of content to complete, and each student completed this content at his/her own pace depending on the number of trials attempted and errors made. As such, each student completed different amounts of content. All 25 students in the training group completed the language/listening series, and advanced to varying levels of the reading series. Attendance, which is the number of days attended relative to the weekdays available during the training period, was 84% (SD = 0.11). Participation, indicating the time on task on the days students were present, was 103% (SD = 0.04), indicating that the average student was sufficiently engaged and motivated by the software to participate for slightly over the required 50 min per day.

A certified English teacher and research assistants who were responsible for assuring compliance with the software's training protocol monitored the training. The teacher completed the training provided by the developers of the software in the use of this software, as well as how to interpret students' daily results in order to provide help for students who were struggling with specific aspects of the program. Students were introduced to the program on the first day of training and practiced each exercise using the demonstration examples provided with the software to assure they understood each exercise. Each day thereafter, students accessed a computer in the lab and entered their password to start the program. The passwords assured that each student's data were retained and uploaded to the software's progress monitoring tools after each session. As a result, the program started each subsequent session where the student stopped the previous session.

Each exercise is individually adaptive, moving to harder items based on correct responses and back to easier items based on errors. The exercise progression algorithm aimed to keep each student performing at approximately 80% correct and students had to master easier content items before moving to more difficult items. Thus, the percent of content completed in each exercise, rather than percent correct, was the data of interest. The software's progress monitoring tools kept daily records of each student's percentage of completion on each exercise and prompted the teacher as to when the student had completed the language/listening program and was ready to begin the reading series. The teacher also received real-time feedback in the form of daily progress graphs and detailed reports of errors that indicated need for intervention. The software's online data management system provided red flags to the teacher that pinpointed individual students who were struggling with specific exercises. As part of the accepted best practices in the use of this software, the teacher and research assistants were trained how to use this online progress monitoring system and encouraged to interact with students based on this feedback. The daily progress reports gave the teacher explicit suggested interventions she could use to help the student progress through the content in each exercise. While the teacher was assisting an individual student, research assistants circulated throughout the lab monitoring student progress.

ASSESSMENT MEASURES

Gates MacGinitie reading test

Students' reading comprehension was measured by the fourth edition of the online version of the comprehension subtest of the Gates MacGinitie Reading Test (GMRT) (MacGinitie et al., 2010). The GMRT is a timed, group-administered assessment of reading comprehension. The Adult Reading (AR) level of the test can be administered on more than one occasion, alternating between forms S and T. Alternate form reliability is reported as 0.83. The AR comprehension section consisted of 11 expository and narrative passages, each followed by three to six multiple-choice questions, for a total of 48 questions. Students read each passage silently and then answered three to six multiple-choice questions related to the most recently read passage. Items increased in difficulty as the student progressed through the test during the 35-min time limit. Internal consistency reliability is reported as 0.85.

Oral and written language scales written expression scale

Students' writing was measured by the OWLS Written Expression Scale (Carrow-Woolfolk, 1996). The OWLS Written Expression Scale is a standardized assessment of written language skills that can be administered individually or in small groups to individuals 5 through 21 years of age. The OWLS Written Expression Scale was chosen because of its high reliability and relevancy to authentic writing. The *OWLS Manual: Written Expression Scale* reports a test-retest evaluation with 9 weeks between administrations and found no improvement on the students' scores at any age. The internal consistency of the OWLS Written Expression Scale was 0.88; test-retest reliability was 0.88; and inter-rater reliability was 0.95. In addition to its high reliability, the OWLS Written Expression Scale addresses the elements of writing commonly assessed in standardized high stakes tests. These elements include use of content (meaningful content, details, relevance, coherence, supporting ideas, word choice, and unity), linguistics (modifiers, phrases, question forms, verb forms, and complex sentence structure), and conventions (spelling, letter formation, punctuation/capitalization, and conventional structures). Items on the assessment consisted of both structured and open-ended writing tasks that represent typical writing activities found in the classroom, thus providing a broad and extensive sample of an individual's writing skills. For example, in one question, students are asked to write a paragraph describing why they prefer cats or dogs. Another question asks students to describe a bicycle to an alien using a single, well formed sentence. Yet another question provides data in a table for students to interpret and asks the students to write a paragraph describing these data.

DATA ANALYSIS

In the current study, the GMRT and OWLS Written Expression Assessment were administered to all participants, both before (Time 1) and after (Time 2) the training group received the training. Different versions of the same test were available for the GMRT, but not for the OWLS. The GMRT was scored automatically by a computer automated scoring program provided by the

test developer. Computer automated scoring of the OWLS Written Expression Assessment was not available. Rather, the OWLS requires a trained professional experienced in scoring this test using the standardized rules and examples explained in the *OWLS Manual* to score each item. To increase reliability and reduce potential bias in this study, the training group and comparison group's tests were intermixed so that the scorer was blind to whether they were scoring a training or comparison group subject. To increase consistency in scoring, individual student's Time 1 and Time 2 tests were scored together. However, the order of scoring Time 1 and Time 2 tests was randomized so that the scorer did not know which test was being scored at any time, Time 1 or Time 2. To further ensure consistency, the tests were scored methodically, scoring all of question 25 for all subjects, and then all of question 26, and so forth. Thus, during the scoring process the scorer was blind to whether they were scoring a response from a trained or comparison subject or from Time 1 or Time 2. As per instructions in the *OWLS Manual*, raw scores were converted to grade-based norm standard scores ($M = 100$, $SD = 15$).

A total of 106 Time 1 and Time 2 tests were scored for 53 subjects (25 training; 28 control). Two scorers experienced in scoring the OWLS Written Expression Scales participated in scoring the data for this study. Scorer A scored all tests. A second scorer (Scorer B) scored a selection of a total of 48 tests (the Time 1 and Time 2 tests of 24 study participants; 12 randomly selected from the training group and 12 from the comparison group). A Pearson correlation coefficient was calculated for the relationship between the two raters' scores. A strong positive correlation was found [$r (46) = 0.71$, $p < 0.01$]. Next, all discrepancies were discussed between Scorer A and Scorer B, with reference back to the *OWLS Manual*, and a True score was determined. The vast majority of discrepancies centered on a small number of items. Each of those items were discussed and resolved between Scorer A and B and then those items were rescored for all subjects. The final correlation coefficient between Scorers A and the True score was [$r (46) = 0.96$, $p < 0.01$].

To examine the extent to which training affects changes in literacy measures, standard scores of the GMRT, and OWLS were first submitted to separate 2×2 mixed-model analyses of variance (ANOVAs), with the between-subjects factor being Group (training vs. comparison) and the within-subjects factor being Time (1 vs. 2). In a second step, we explored the effects of ESL on GMRT and OWLS outcomes by conducting 2 (ESL; no vs. yes) $\times$ 2 (Time; 1 vs. 2) mixed-factor ANOVAs. Because of the small number of ESL students in the comparison group, these analyses were restricted to the members of the training group. Partial eta-squared (η_p^2) values were reported as a measure of effect size (Cohen, 1988). Where appropriate, contrast analyses were used to follow-up significant ANOVA results. For all statistics, effects were deemed significant when $p < 0.05$.

RESULTS

Demographic characteristics and standardized literacy scores for the training group and comparison group are shown in **Table 1**. Students in the training group demonstrated systematic gains in both reading and writing skills following training. For the GMRT reading assessment, the two-way ANOVA revealed that

Table 1 | Demographic characteristics and standardized literacy measures by participant group.

	Training group	Comparison group
Sample size	$n = 25$	$n = 28$
Gender (male/female)	8/17	12/16
ESL (no/yes)	12/13	22/6
Age (years)	20.08 ± 3.57	19.39 ± 1.37
GMRT time 1	109.31 ± 11.77	113.19 ± 13.38
GMRT time 2	113.33 ± 13.03	112.05 ± 14.12
GMRT difference time 1 vs. 2	$p < 0.031$	$p < 0.508$
OWLS time 1	86.20 ± 9.68	98.11 ± 14.84
OWLS time 2	111.04 ± 15.88	95.61 ± 17.40
OWLS difference time 1 vs. 2	$p < 0.001$	$p < 0.326$

Means ± standard deviations are shown; p-values are based on contrast analyses with a significance level set to 5%. ESL, English as a second language; GMRT, Gates MacGinitie Reading Test; OWLS, oral and written language scales, written expression scale.
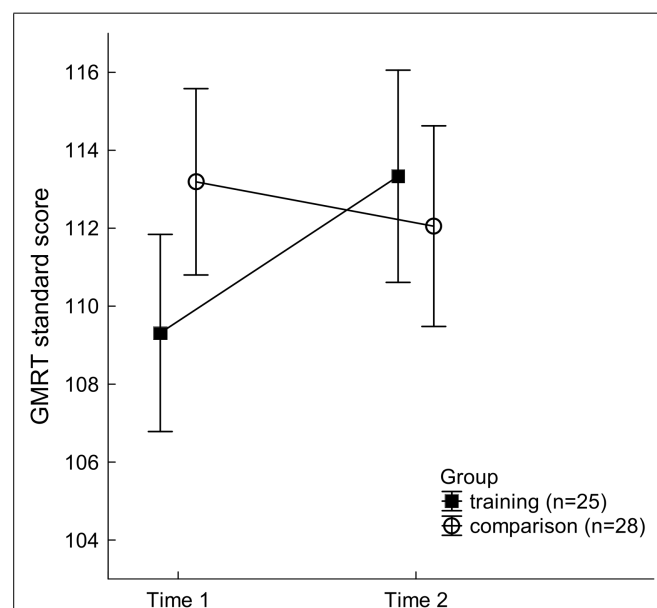

FIGURE 1 | Gates MacGinitie Reading Test (GMRT) standard scores for the two participant groups at Time 1 and Time 2. Mean values of 25 training group students (filled squares) and 28 comparison students (open circles) are depicted. Vertical bars represent standard errors of mean. While there was no significant change in reading performance in the comparison group, GMRT scores in the training group increased significantly from Time 1 to Time 2.

main effects of factors Group and Time did not reach statistical significance. However, there was a significant Group $\times$ Time interaction, $F(1, 51) = 4.31$, $p < 0.043$, $\eta_p^2 = 0.08$ (see **Figure 1**). As evaluated by focused contrasts, this interaction was accounted for by significantly better reading scores at Time 2, post-FFW training, compared to Time 1, pre-FFW training, in the training group only, $F(1, 51) = 4.96$, $p < 0.031$.

For the OWLS Written Expression Scale, a significant main effect of Time was found, $F(1, 51) = 37.14$, $p < 0.001$, $\eta_p^2 =$

0.42, demonstrating that writing scores increased from Time 1 (mean $\pm$ SEM; 92.15 $\pm$ 1.74) to Time 2 (103.32 $\pm$ 2.30) across both groups. This was, however, mainly driven by the performance changes of the training group participants as evinced by a significant Group $\times$ Time interaction, $F(1, 51) = 55.63$, $p < 0.001$, $\eta_p^2 = 0.52$ (see **Figure 2**): follow-up contrasts indicated that the training group participants achieved significantly higher writing scores at Time 2, upon completion of FFW training, than they had at Time 1, before FFW training, $F(1, 51) = 86.93$, $p < 0.001$. No comparable improvement was found for the comparison group. Further, at the onset of the study (Time 1) the writing scores of the training participants were significantly lower than those of the comparison group, $F(1, 51) = 11.65$, $p < 0.002$. However, at Time 2, after the training group had completed the FFW training programs, their considerable improvement in writing led to a reversed performance pattern, with the trained group's standard scores on the OWLS now significantly exceeding those of the comparison group, $F(1, 51) = 11.28$, $p < 0.002$.

Reading and writing skills in the training group were systematically modulated by whether a student was a native English speaker or English was their second language (ESL). Although the mixed-model ANOVA on GMRT values resulted in a significant main effect of Time, with better scores at Time 2 (113.55 $\pm$ 2.42) than Time 1 (109.35 $\pm$ 2.40), $F(1, 23) = 6.66$, $p < 0.017$, $\eta_p^2 = 0.22$, this was subordinate to a two-way interaction with factor ESL, $F(1, 23) = 7.72$, $p < 0.011$, $\eta_p^2 = 0.25$ (see **Figure 3**). As can be seen in **Table 2**, native speakers of English improved significantly on the GMRT reading comprehension test across visits,

$F(1, 23) = 13.81$, $p < 0.002$, and outperformed the trained ESL group after completion of the training, $F(1, 23) = 4.96$, $p < 0.037$. For the OWLS, significant main effects of ESL, $F(1, 23) = 11.47$, $p < 0.003$, $\eta_p^2 = 0.33$, and Time, $F(1, 23) = 80.33$, $p < 0.001$, $\eta_p^2 = 0.78$, were observed. Writing scores were higher overall in non-ESL than ESL speakers (105.04 $\pm$ 2.63 vs. 92.69 $\pm$ 2.53) and generally higher at Time 2, after FFW training than at Time 1, for both groups (111.39 $\pm$ 2.68 vs. 86.34 $\pm$ 1.83). These results show that the training led to significant improvement in writing for both ESL and non-ESL college students. The ESL $\times$ Time interaction failed to reach significance, $F(1, 23) = 3.46$, $p < 0.076$, $\eta_P^2 = 0.13$ As illustrated in **Figure 4**, while native speakers of English tended to exhibit somewhat greater enhancement in writing than the ESL group following FFW training, this difference did not reach significance.

DISCUSSION
SUMMARY OF RESULTS
Overall this study provides evidence that both the reading and writing abilities of college students can be rapidly and substantially improved through the use of a series of neuroplasticity-based cognitive and linguistic training programs (FFW-L and Reading levels 3–5). College students who began the study with writing scores approaching a full standard deviation below the mean of average, based on a standardized, authentic writing assessment (OWLS, Written Expression Scale), who had been recalcitrant to traditional academic writing instruction approaches, showed significant improvement in writing after completing 11 weeks of
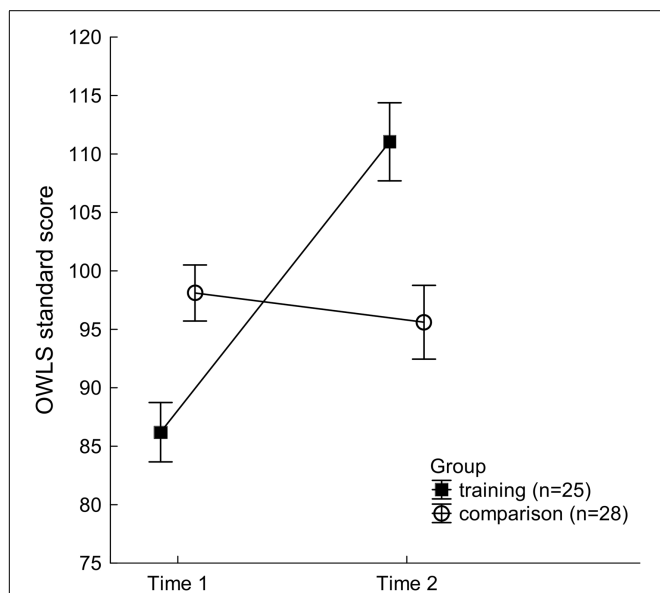

FIGURE 2 | Written Expression Scale standard scores of the Oral and Written Language Scales (OWLS) for the two participant groups at Time 1 and Time 2. Mean values of 25 training group participants (filled squares) and 28 comparison participants (open circles) are shown. Vertical bars indicate standard errors of mean. While the training group students were outperformed by the comparison group at Time 1, their considerable spurt in writing following intervention, led to a reversed performance pattern at Time 2, with lower standard scores in the non-trained students.
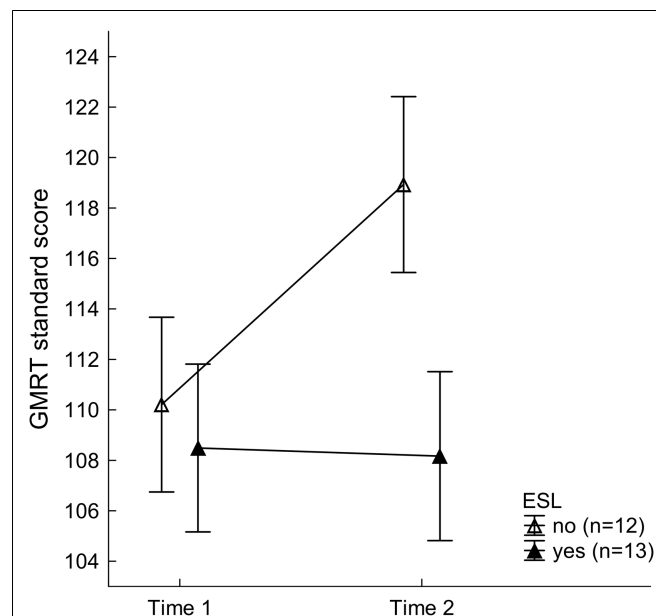

FIGURE 3 | Gates MacGinitie Reading Test (GMRT) standard scores for the training group as a function of speaking English as a second language (ESL) at Time 1 and Time 2. Mean values of 12 non-ESL (open triangles) and 13 ESL students (filled triangles) are shown. Vertical bars represent standard errors of mean. Non-ESL training participants improved significantly across time and outperformed the ESL students after completion of the intervention protocol.

Table 2 | Demographic characteristics and standardized literacy measures for the training group as a function of speaking English as a second language (ESL).

	ESL: no	ESL: yes
Sample size	$n = 12$	$n = 13$
Gender (male/female)	4/8	4/9
Age (years)	20.50 ± 4.76	19.69 ± 2.10
GMRT time 1	110.21 ± 10.70	108.49 ± 13.07
GMRT time 2	118.93 ± 13.96	108.17 ± 10.04
GMRT difference time 1 vs. 2	$p < 0.002$	$p < 0.889$
OWLS time 1	89.92 ± 6.69	82.77 ± 10.95
OWLS time 2	120.17 ± 15.28	102.62 ± 11.39
OWLS difference time 1 vs. 2	Not applicable	Not applicable

Means ± standard deviations are shown; p-values are based on contrast analyses with a significance level set to 5%; due to a non-significant Time × ESL interaction, post hoc contrasts were not applicable for the OWLS. GMRT, Gates MacGinitie Reading Test; OWLS, oral and written language scales, written expression scale.
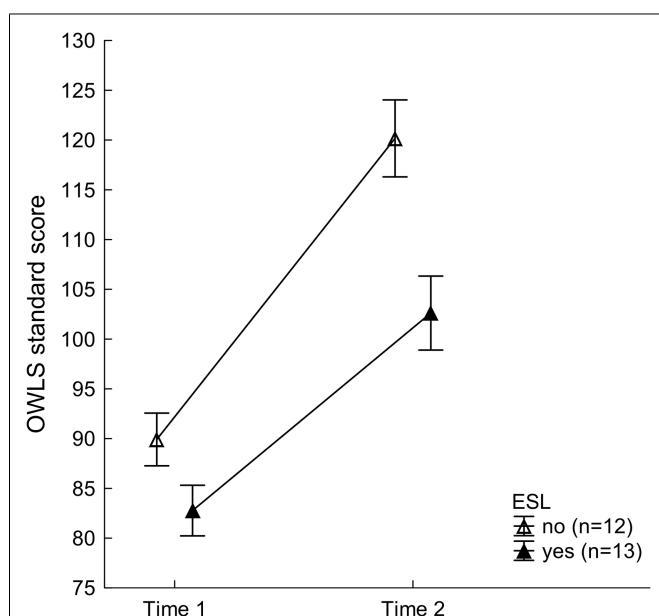

FIGURE 4 | Written Expression Scale standard scores of the Oral and Written Language Scales (OWLS) for the training group as a function of speaking English as a second language (ESL) across the two time points. Mean values of 12 non-ESL (open triangles) and 13 ESL students (filled triangles) are depicted. Vertical bars indicate standard errors of mean. Non-ESL participants tended to exhibit somewhat greater improvement in writing following training than ESL speakers. This difference, however, failed to reach statistical significance.

daily training. These results show that from pre-training to post-training these students improved their writing abilities by one and two thirds standard deviations, moving from below to above average writing scores. A comparison group of college students with average writing scores, who did not receive training, showed no significant test-retest change in their writing scores over a comparable period of time. Results showed that at the onset of the study the writing scores of the training group participants were significantly lower than those of the comparison group. However, after the training this pattern of performance was reversed, with the trained group's standard scores on the OWLS written expression scale now significantly exceeding those of the comparison group. The reading ability of these students was also assessed both before (pre-test) and after (post-test) the students with weak writing skills participated in the training program. It is of interest that the students with weak writing skills performed well within the normal range on reading at pre-test, albeit lower than the comparison group, on a standardized reading test (GMRT). At post-test the reading scores of the comparison group did not change while those of the group that received the training improved significantly.

Half of the students who entered the study with weak writing skills were native English language speakers while the others spoke ESL. These subgroups responded somewhat differently to the training. Both groups scored above average on the GMRT reading test before training. However, only the native English speakers showed significant gains in reading after training. The results for writing outcomes showed a different pattern. While both subgroups entered the study with substantially below average writing abilities as measured by the OWLS Written Expression Scales, the ESL student's writing skills were lower than the native English speakers at pre-test. However, both the native and ESL speakers showed substantial benefits from the training, with both groups significantly improving their writing performance at post-test.

THEORETICAL IMPLICATIONS

The computerized training programs used in this study were developed based on a neurodevelopmental model that posits a continuum from perceptual/cognitive abilities, to spoken language abilities to written language abilities. Early perceptual and cognitive skills (attention, processing speed, sequencing, memory) are reported frequently in the research literature as concomitant individual differences in young children that correlate with and predict individual differences in language development (Heim and Benasich, 2006; Benasich and Choudhury, 2012). For example, Benasich and Tallal (2002) have shown that thresholds in the speed of auditory processing obtained in infancy are highly predictive of subsequent language expression and comprehension in preschool children. Similarly, it has been shown that spoken language development is highly predictive of early reading development and disorders (Flax et al., 2009). There also is a well-established relationship between individual differences in early reading and writing skills (Fitzgerald and Shanahan, 2000). Based on these relationships Tallal and colleagues posited a continuum between perceptual/cognitive abilities, particularly auditory processing speed, spoken language development, and written language development (Tallal, 2004). The Fast ForWord series of training exercises were developed specifically with this continuum in mind to help students struggling with language and literacy skills. The exercises are designed to go back to first principles of clarifying the neural representation of sounds within syllables, words and sentences as well as explicitly gaining mastery over all of the rules of English grammar. Training of these basic skills is presented within a context of a highly systematic and developmentally informed series of exercises that progressively challenge linguistic as well as

processing and cognitive skills. This is done within the context of spoken language only (Fast ForWord-Literacy) until the student achieves a high level of mastery over the content across all exercises. Only then is the student introduced to exercises that include written material (Fast ForWord Reading Series). Like the spoken language exercises, the exercises in the reading series have been designed to follow a developmental trajectory ranging from phonemic awareness, to morphological awareness, to increasingly challenging aspects of reading comprehension within simple sentences to complex texts. Across all exercises, neuroplasticity-based learning principles are used to drive individually adaptive increases in performance, mouse-click-by-mouse-click. According to these learning principles, neuroplasticity is driven most efficiently by frequent and intense practice, sustained attention, individually adaptive trials (from easy to harder), and highly timed rewards and correction of errors (immediately following each response). Students progress at their own pace along a defined trajectory from easier items with lower cognitive load to items that are progressively more challenging both linguistically and cognitively. Students do not progress to harder more challenging items until they have shown a very high degree of mastery of easier items and levels.

When first examining the actual exercises included in the FFW-L and Reading training exercises, which are presented like repetitive video games, most teachers would likely consider them far too elementary to help secondary students, much less those who have been admitted to college, but are, nonetheless, struggling with writing. Intervention for students at this level generally focuses at a much higher level of content analysis and comprehension, organizational skills, and writing strategies for integrating newly learned materials into a cogent essay. It is assumed that by the time children move beyond elementary and middle school they have sufficient basic cognitive skills and have acquired proficiency in the basic linguistic skills and formal writing conventions they will need to handle the increasingly complex reading and writing demands placed on them in high school and college. However, based on standardized high stakes tests, this is not the case for an increasing majority (73% according to the 2012 NAEP results) of U.S. students. These numbers are even more discouraging for underrepresented minority and ESL students. The results of this study demonstrate the significant benefits of providing basic cognitive and linguistic skills remediation as an adjunct to more traditional methods for improving literacy skills in struggling students, well beyond the elementary school years.

COMPARISON WITH PREVIOUS STUDIES

Not all studies that have used the Fast ForWord training approach have shown significant improvement in literacy. However, this study differed from previous studies in several ways. This is the first study to focus on college students. The study is also the first to focus on improving writing as well as reading. Furthermore, unlike previously published studies, this study used the full series of the Fast ForWord language and reading training programs, providing individually progressive training aimed at strengthening basic auditory processing and cognitive skills (memory, attention, processing speed, sequencing), spoken language skills (from phonology to syntax), reading skills (ranging from syllable, to word, to multiple

paragraphs), to basic writing conventions (including spelling patterns and punctuation). Finally, it is important to emphasize that Fast ForWord differs from most other forms of computerized intervention in that it was not designed to be a stand alone software program. The intensity (5 days per week), fidelity to protocol, and student/monitor interaction required to achieve positive outcomes all require that the program be provided by an experienced Fast ForWord provider. Individual subject's Fast ForWord performance on each exercise is analyzed daily *via* an electronic progress tracker. When used in clinics and classrooms, trained providers receive "red flags" that alert them to students who are experiencing problems on specific aspects of the training and have been trained how to intervene to correct these problems so that students can progress in the program. Studies that have not used a trained monitor who is experienced in providing this additional student support may have failed to get the full benefit of the intervention. This study benefited by having a highly trained and experienced Fast ForWord provider overseeing the daily implementation and student support.

LIMITATIONS

There are several limitations to this study. This was not a randomized controlled trial. The study employed a quasi-experimental design in order to study the effects of cognitive, language, and reading training on the reading and writing skills of college students who were struggling with writing and compared them to a control group of average readers from the same university who did not receive training. The disadvantage of a quasi-experimental design is that groups are not equated on variables of interest at baseline and assigned randomly to receive the same treatment. As such, pre-specification of controls and other experimental variables are not able to be included to support strong statistical inferences. Subjects were recruited into the training group from two populations of students who historically are at risk for lower writing scores: students in developmental writing classes and underrepresented minority STEM majors. All students who volunteered to participate from these two groups were included in the training group. There was no attempt to include or exclude students who had a previous or current diagnosis of dyslexia or other learning disabilities. The comparison group received the same pre-tests and post-tests at the beginning and end of the study, but did not participate in any training or come to the lab daily during the semester. While this comparison group provided control for any changes that might occur from taking the reading and writing test more than once, as well as changes that might occur over a college semester, the effect of differential contact with the research staff across the course of the study cannot be assessed. The training group came to the study lab and completed 50 min of training 5 days a week for a full semester (11 weeks). There was no attempt to evaluate different durations of intervention. Furthermore, the experimental group received only one form of training in this study. Previous studies with younger students have demonstrated that it may be the intensity of training, rather than the specificity of the type of training that is most important for driving improvements in language and literacy (Gillam et al., 2008). It is not possible, therefore, to determine that the significant improvements in reading and writing found in this study are specific to the Fast ForWord

program, specific to students struggling with writing, or the extent to which they may have been achieved by other training programs that were equally intensive. It is also not possible to determine the extent to which these results may be affected by the age of the students. Finally, a limited number of standardized tests were used as outcome measures. While these are well standardized tests that sample a broad range of authentic reading and writing skills, it will be important to replicate these results with other measures, particularly those assessing classroom performance. Further research will be needed to address these important variables. Specifically, it will be important to replicate these results using a randomized controlled study design as well as to determine the extent to which they may apply to younger students or be achieved by other methods. Finally, significant improvements in reading and writing were found immediately following training. It will be important to do follow-up testing over time to determine the longer-term effects of supplementing traditional college instruction with computer-based interventions for improving reading and writing outcomes in struggling students.

CONCLUSION

By the time students reach college it is assumed, often incorrectly, that they do not need instruction or practice in basic language, reading, and writing skills. Rather, they are bombarded with increasingly complex lectures, reading, and writing assignments in virtually all of their courses. At the same time it is not unusual to hear college professors bemoan the fact that many of their students are unable to string two complex sentences together correctly, much less read and analyze complex material and write cogent papers synthesizing new knowledge and expressing their own thoughts and ideas. While many universities are offering developmental writing courses, these rarely focus on taking struggling students back to the basics and progressing systematically to higher levels.

The results of this study demonstrated that a neuroplasticity-based, computer training program, designed initially for younger struggling students to improve basic cognitive, language, and reading skills (Fast ForWord), could successfully be implemented in a college setting to help college students with below average writing abilities rapidly achieve above average writing skills. The results of this study support the efficacy of systematic, progressive perceptual/cognitive, language, and reading skills training for struggling students beyond the primary and secondary school level, as shown here in a college sample. This study also validates the positive benefits of using computer intervention strategies in college students that provide them with a concise, controlled, and individually adaptive means of significantly improving their basic language and literacy skills in a manageable amount of time, without unduly interfering with their intense program of college classes.

It is important to note that no explicit practice with writing *per se* is included in the training programs used in this study. Thus, the results of this study demonstrated that training in basic cognitive, listening, and reading skills generalize to improved writing ability. Our research design did not allow us to distinguish which of the many skills included in the training led to these improvements in writing. Future research is needed to determine the extent to which specific cognitive, language, or reading skills included within the series of training programs used in this study had the most impact on writing.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/Educational_Psychology/10.3389/fpsyg.2013.00137/abstract

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Group rhythmic synchrony and attention in children

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Synchrony, or the coordinated processing of time, is an often-overlooked yet critical context for human interaction. This study tests the relationship between the ability to synchronize rhythmically in a group setting with the ability to attend in 102 elementary schoolchildren. Impairments in temporal processing have frequently been shown to exist in clinical populations with learning disorders, particularly those with Attention Deficit Hyperactivity Disorder (ADHD). Based on this evidence, we hypothesized that the ability to synchronize rhythmically in a group setting—an instance of the type of temporal processing necessary for successful interaction and learning—would be correlated with the ability to attend across the continuum of the population. A music class is an ideal setting for the study of interpersonal timing. In order to measure synchrony in this context, we constructed instruments that allowed the recording and measurement of individual rhythmic performance. The SWAN teacher questionnaire was used as a measurement of attentional behavior. We find that the ability to synchronize with others in a group music class can predict a child's attentional behavior.

Keywords: attention, synchrony, music cognition, temporal processing, learning

INTRODUCTION

The ability to attend is among the most important skills that children must develop and refine. In an interpersonal context, the ability to attend may be related to the ability to synchronize, which we define as the generation of behaviors in coordination with an external stimulus at specific points in time. Co-attention with a parent emerges in infancy (Deák et al., 2000; de Barbaro et al., 2000) and naturally requires an infant to synchronize, directing gaze, and orientation nearly in unison with the parent. Later, in more complex forms of interaction such as conversation, the ability to synchronize facilitates smooth transfer of information (Bernieri and Rosenthal, 1991).

Studies of attention deficit hyperactivity disorder (ADHD) suggest a link between attention and temporal processing, as reviewed by Toplak et al. (2006). Children with ADHD who by definition display inattentive behavior have been shown to perform more poorly than controls on a variety of temporal processing tasks, such as duration discrimination, duration reproduction, anticipation tasks, and finger tapping tasks (Gilden and Marusich, 2009). Impaired temporal processing has been posited as a cognitive marker of ADHD (Castellanos and Tannock, 2002). Similarly, variability in response times, or reaction time variability (RTV), has been identified as increased in ADHD across a variety of tasks and contexts (Gilden and Marusich, 2009; Klein et al., 2006).

A useful measure of temporal processing can be found in rhythmic components of the practice of music. Rather than referring specifically to "beats," rhythm in music refers to any form of temporal pattern, regardless of the presence of "beats." Playing music requires one to maintain synchrony across multiple nested timescales, from tens of milliseconds to minutes.

In particular, theoretical work suggests that synchronizing with an isochronous beat—a basic musical skill—requires the perception and estimation of time intervals in the order of 10 ms to 1000 ms. (Repp, 2005; Jacoby and Repp, 2012). The familiar context of a group music class may be an efficient and ecologically-valid method of measuring children's ability at such tasks.

The aim of this study was to examine the relationship between temporal processing, as measured by the ability of a child to synchronize to a driving beat, in the context of a music class, and attentional behavior, measured by teacher ratings. While the link between temporal processing and attentional behavior has been confirmed in samples diagnosed with ADHD, we do not yet know how temporal processing relates to attention in the general population. Based on the previous literature, we hypothesize that the ability of children to synchronize is correlated with their attentional behavior.

In order to measure the ability to synchronize, we use specially-wired instruments that allow detection of each mallet strike of each player. In order to measure attentional behavior, we use teacher ratings of the Strengths and Weaknesses of ADHD and Normal Behaviors (SWAN) questionnaire (Swanson et al., 2006). This DSM-IV based questionnaire was developed to assess ADHD-like symptoms across the continuum of children's behavior (rather than at the extreme, maladaptive end). We also included cognitive-performance measures (mean reaction time, RTV and errors) from a task that is often used in attentional and ADHD research, the Eriksen Flanker Task (EFT; Albrecht et al., 2008).

MATERIALS AND METHODS

OVERVIEW

Participants were scored along three different dimensions. Synchrony, pertaining to measurement of musical timing, the SWAN teacher rating questionnaire, which includes a behavioral measure of attention (Swanson et al., 2006), and the Eriksen flanker task, a computerized psychometric task often used to measure attentional control (Eriksen, 1995).

Our assessment of participants' rhythmic synchrony was conducted in a context that reflected a typical music class. Groups of roughly 12 participants playing five-keyed metallophones were seated in a semi circle facing a leader. The leader played a beat on a non-pitched percussion instrument. The synchrony of each participant was assessed [defined] against this beat.

A musical beat can be described by the movement of a point around the perimeter of a circle. The location of this point with respect to the center of the circle defines an angle. When playing an isochronous pulse, the exact time of the leader's onsets (mallet strikes) corresponds to an angle of 0, the quarter beat to an angle of $\pi/2$, the offbeat to π, and so forth. We calculated this time-dependent angle (or phase) based on the leader's onsets. We then calculated each participant's onsets and analyzed the distribution of the angles of their individual mallet strikes. The more narrow the distribution of angles, the more regular in relation to the leader a participant's playing. Such a player would be ranked more highly than one with a wider distribution of angles.

We then calculated the correlation of within-group synchrony rankings with attention behavior, as measured by the SWAN questionnaire and the Eriksen flanker task. In order to do this we calculated the correlation coefficients between the different measures. We corrected for performance differences across grades and genders by using them as covariates.

PARTICIPANTS

We tested 102 students from grades 2–6 (**Table 1**) at the Museum School, a charter school in San Diego, CA. The ethnic composition of the participants was as follows: White 43%, Hispanic 31%, African American 13%, Asian/Pacific Islander 13%. Fifty-six percent were female. The number of students in each grade can be seen on **Table 1**. All of the participants had previous experience with musical training, as it was one of their curriculum classes (30 min-classes, once a

week) and Dr. Khalil was their teacher. Here, it is important to note that Khalil is an ethnomusicologist with 25 years experience studying and/or teaching traditional Balinese gamelan music. Thus, despite his cross-training in behavioral and computational neuroscience (expertise held by the other members of the team), he approaches the classroom as a seasoned instructor.

RHYTHMIC SYNCHRONY

Gamelan is a musical art form that strongly emphasizes rhythmic synchrony among the ensemble members. A gamelan ensemble is made up of pitched percussion instruments with bronze keys. The instruments used for testing rhythmic synchrony were modeled after gamelan instruments, see **Figure 1**.

The gamelan-like instruments we designed and constructed feature piezoelectric film elements applied to each key. The importance of this innovation is that it allows each mallet strike on each key, for each player, to be recorded individually and in isolation in a temporally precise manner (details below). The instrument played by the instructor has a distinctively different timbre, or harmonic profile, than the ones used by participants.
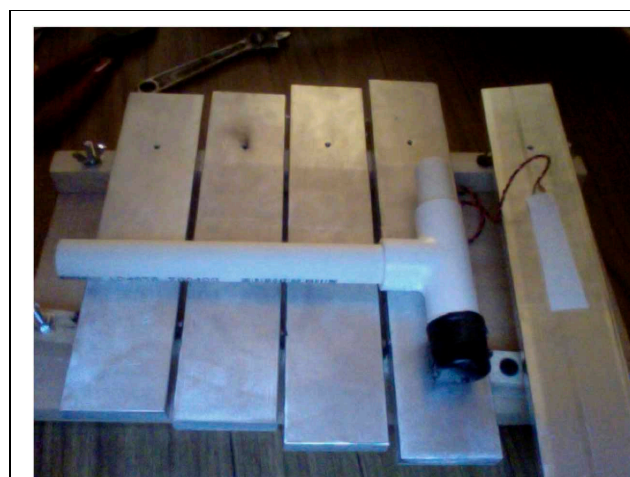

FIGURE 1 | Example of musical instrument constructed for this study. These pitched-percussion instruments have a piezoelectric film element affixed to each key. This allows isolated recording of each instrument.

Table 1 | Descriptive statistics.

Grade	Participants	VS	SWAN I	SWAN C	CONG	INC	RT CONG	RT INC	RTV CONG	RTV INC	RTD
2	21	0.869 (0.13)	−4.52 (11)	−7.1 (22)	0.808 (0.18)	0.634 (0.18)	485 (78)	568 (1e + 02)	152 (59)	166 (78)	82.7 (40)
3	16	0.894 (0.054)	3.31 (7.9)	3.92 (15)	0.869 (0.11)	0.607 (0.21)	455 (90)	527 (91)	117 (53)	124 (38)	71.5 (17)
4	24	0.854 (0.095)	−2.48 (13)	−10 (26)	0.784 (0.2)	0.575 (0.23)	411 (69)	488 (73)	144 (63)	157 (92)	76.9 (32)
5	23	0.915 (0.041)	−3.62 (12)	−16.8 (23)	0.839 (0.19)	0.601 (0.24)	387 (79)	459 (90)	96.7 (31)	106 (55)	71.9 (23)
6	18	0.944 (0.02)	−0.667 (7.1)	−3.5 (13)	0.856 (0.2)	0.568 (0.23)	369 (60)	446 (54)	96.6 (52)	98.4 (54)	77.2 (25)

Average values of the different variables by grade, standard deviations in parenthesis. SWAN I and SWAN C are the mean scores in the mainly inattentive and mainly hyperactive SWAN questionnaires respectively. CONG and INC stand for proportion correct in the congruent and incongruent conditions respectively. RT is reaction time (in ms), RTV is within participant variability in reaction time, measured as standard deviation of reaction times. RTD is the difference in reaction time in the incongruent vs. congruent conditions.

Participants within each grade (2–6) were divided into two groups of equal size; if the number of participants within a particular grade was odd, one of the groups would have one more member. Participants were recorded as they attempted to synchronize with an isochronous beat played by the instructor over 1 min. Because our interest was in recording participants while engaged in the task, rather than recording them over a long period—during which time many participants could become disengaged—we repeated this process four times, interleaving these episodes with other musical activities across a 30-min recording session.

We calculated the synchrony between each player and the leader according to the following procedure. We first calculated each participant's onsets. In order to find the onsets of the leader we ran a complex filter on the audio signal at 200 Hz (50 Hz bandwidth) and took its absolute value. This process revealed clear peaks coinciding with the onsets. A threshold was chosen by hand through visual inspection based on the individual records. The first time a peak crossed the threshold was considered the time of the onset. If two peaks were observed over a period of 200 ms. we considered only the first one. We adopted this criterion in order to avoid counting "double-hits" caused by mallet bounce. A similar procedure was used to find the participants' onsets, except that 500 Hz (50 Hz bandwidth) was used as the filtering frequency due to the higher fundamental and harmonic profile of the participants' instruments.

We next calculated the phase of the leader. In order to do this we ran a complex filter on the leader's onset data centered on 1 Hz (bandwidth .75 Hz) and took the angle of the resulting signal. This produced a time-dependent phase signal that was 0 on the beat and π on the off-beat. A set of phases for each participant was collected by evaluating the phase signal obtained from the leader at each participant's onset times, or mallet strikes.

In order to measure the acuity of each participant's synchrony, we performed a vector strength (VS) analysis. This measure was introduced by Goldberg and Brown (1968) and has been extensively employed to analyze synchrony of neural activity.

VS is defined as follows:

$$VS = \frac{1}{N} \left| \sum_{j=1}^{N} e^{i^* \varphi j} \right|$$

Where N is the total number of onsets of one participant, j is the onset number, φ is the corresponding phase, and i is the imaginary unit. Thus, defined, VS is 1 if the participant always plays with the same phase with respect to the driving beat and 0 if she or he plays randomly. For each participant, we calculated the average VS across all four synchronization episodes.

VS more accurately reflects the ability to synchronize in a class setting than others that have been used for similar work, such as inter-tap variability. This is because it remains unaffected if a player misses a few beats or if the lead player changes tempo.

ERIKSEN FLANKER TASK

The Eriksen Flanker Task (EFT; Eriksen, 1995) was administered to each participant. Each participant was asked to press a key with their left or right index finger when a central arrow (target) appeared in the middle of the screen pointing in the corresponding direction. 100 ms before the target, two flanking distractor arrows appeared that pointed either in the same (congruent condition) or opposite (incongruent condition) direction as the target arrow. We computed the percentage of correct responses as the number of correct responses over the total number of presentations for each condition (congruent and incongruent). For the calculation of reaction time measures we only considered correct responses. We calculated the mean reaction time for each condition; the RTV, measured as standard deviation; and the reaction time difference across conditions (incongruent—congruent). See below for a list of all variables.

SWAN QUESTIONNAIRE

The Strengths and Weaknesses of ADHD Symptoms and Normal Behavior (SWAN) Rating Scale (Swanson et al., 2006) is a questionnaire of the Likert-type based on the Diagnostic and Statistical Manual of Mental Disorders (4th ed; DSM-IV, APA, 1994). The questionnaire assesses children's behavior along the dimensions of inattention and hyperactivity-impulsivity. It was designed to be sensitive at both the negative and adaptive ends of the two symptom dimensions of ADHD. It was shown to have internal consistency and test-retest reliability (Arnett et al., 2012) as well as external validity (Arnett et al., 2012) as compared with the Disruptive Behavior Rating Scale (DBRS; Barkley and Murphy, 2006).

The SWAN is rated on a balanced 7-point Likert-type scale, with anchors far above, above, slightly above, average, slightly below, below, and far below. For measuring behavioral attention/inattention, SWAN includes items such as: "Compared to other children"…the child … "Sustains attention on tasks or play activities." It is composed of eighteen questions. Nine of them assess attentive behavior (SWAN I) and the other nine address hyperactive-impulsive behavior (SWAN H). Therefore, SWAN I is a behavioral measure of attention. The total questionnaire is referred to as SWAN C, where C refers to inattentive and hyperactive combined and is considered a measure of ADHD-like behavior. This questionnaire was filled out for each participant by the homeroom teacher.

For analyzing the SWAN data, we numbered the anchors from −3 to 3 and calculated the sum for SWAN-I and SWAN-C. Note that high scores on the SWAN-I and SWAN-C are associated with worse attention and more ADHD-like behavior.

STATISTICAL METHODS

All analysis was performed using MATLAB and Statistics Toolbox Release 2012b, The MathWorks, Inc., Natick, Massachusetts, United States.

The variables included in analysis were as follows:

1. The average vector strength (VS).
2. The SWAN questionnaire, inattentive and combined scores (SWAN I and SWAN C).
3. The proportion of correct responses in the congruent and incongruent conditions of the flankers task (CONG and INC).
4. The mean reaction times in the EFT (RT CONG and RT INC).

5. The variability of reaction times in the EFT (RTV CONG and RTV INC).

6. The reaction time difference between the CONG and INC conditions in the EFT (RTD).

In order to evaluate the significance of the *VS* values, we used Rayleigh statistics, as provided by the circular statistics toolbox in MATLAB (Berens, 2009).

The distribution of VS scores was analyzed and found to be highly skewed (-2.9) with long tails revealed by the large kurtosis (13.5). Kurtosis is defined here as the fourth standardized moment of the distribution. Because of the non-normality of the distribution we decided to use the non-parametric Kruskall-Wallis analysis of variance to test differences across groups.

A Kruskall-Wallis test revealed a significant difference in *VS* across grades [$\chi^2_{(4, 97)} = 21.25$, $p < 0.001$]; therefore, we used grade as a covariate. Since VS scores do not vary linearly with grade, we treated grade as a nominal rather than continuous variable.

A Kruskall-Wallis test for differences across the two playing groups within the same grade revealed group differences only for grade 3 [$\chi^2_{(1, 14)} = 7.46$, $p < 0.01$]; therefore, we used playing group as a covariate for grade 3. Categorical and continuous data was combined to evaluate the effect of gender as a possible covariate. A value of 0 was assigned to female participants and a value of 1 to male participants, and the partial correlation between gender and the various scores was calculated (using covariates). Female participants were better synchronizers than male participants, reflected by the fact that gender correlated with VS scores [$r_{(100)} = -0.22$, $p < 0.04$]. Females were also more attentive [SWAN I $r_{(100)} = 0.33$, $p < 0.01$], less hyperactive [SWAN H $r_{(100)} = 0.31$, $p < 0.01$], more accurate on the incongruent flankers [INC $r_{(100)} = -0.27$, $p < 0.02$], and had lower reaction time in the congruent condition [RT CONG $r_{(100)} = 0.26$, $p < 0.02$]. Therefore, gender was used as a covariate in all further analyses.

Using these covariates, we then calculated the partial correlation between VS scores and each of the other variables (SWAN C, SWAN I, CONG, INC, RT CONG, RT INC, RTV CONG, RTV INC, RTD) and analyzed the distribution of the residuals. We found all distributions to be highly skewed (all skewness values were larger in magnitude than -2.2) and to have long tails (all kurtosis were larger than 10). Spearman's rank correlation was used for further analysis since it is more robust. Spearman's method ranks the data. Therefore, the variable distributions become symmetric and the influence of outliers is reduced. Spearman's correlation is generally considered to quantify the degree in which two variables are monotonically related. In the specific case of this study, it quantifies the degree in which better synchronizers tend to be better attenders (SWAN I), or perform better in psychometric task variables proposed to measure aspects of attention (EFT).

In order to evaluate the effect of this transformation, the distribution of residuals was analyzed under Spearman's method: all skewness values were below 0.26 and all kurtosis lay between 2.7 and 3.

The significance of the relationship between the different variables and gender remained in Spearman correlations, so gender continued to be used as a co-variate in our further analyses.

In summary, we ran Spearman's partial correlations using grade, gender, and group (on 3rd grade) as covariates.

RESULTS

All participants in all episodes were significantly synchronized, as assessed by the Rayleigh statistics ($p < 0.05$). **Figures 2, 3** presents an example of a strong synchronizer and a weak synchronizer. **Table 1** shows summary statistics of the different variables for each grade. **Table 2** shows the Spearman correlations between all variables. This is particularly compelling as some of the variables
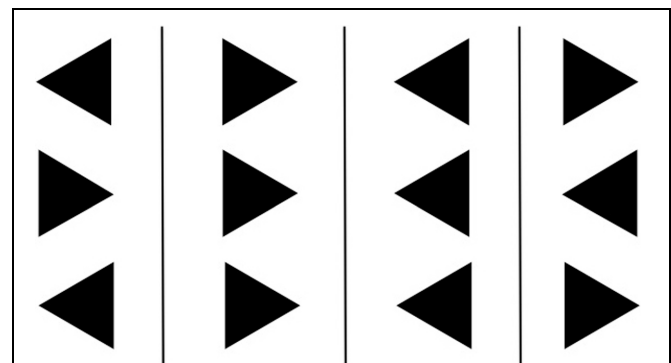
FIGURE 2 | The four sets of stimuli used in the Eriksen Flanker Task.
Left to right: right incongruent, right congruent, left congruent, and left incongruent. The flanking arrows appear 50 milliseconds before the center one.
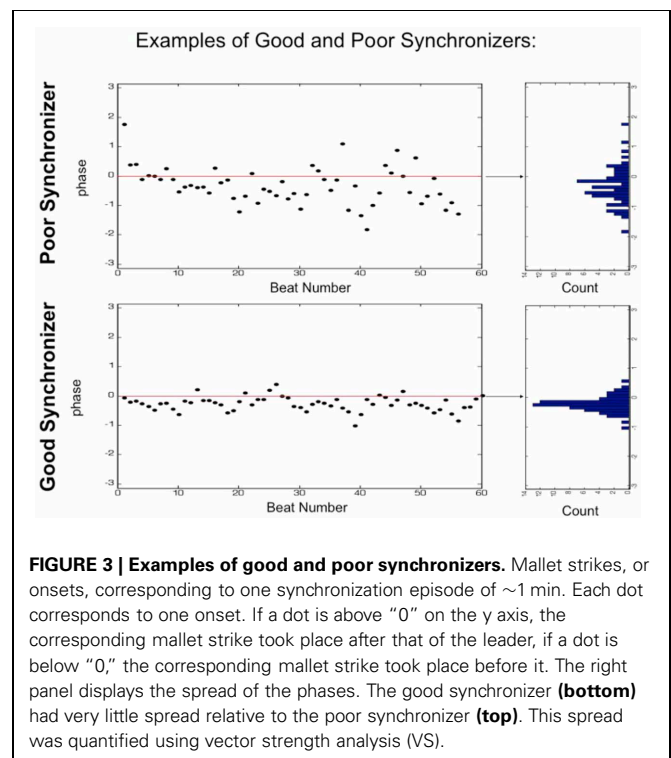
FIGURE 3 | Examples of good and poor synchronizers. Mallet strikes, or onsets, corresponding to one synchronization episode of ~1 min. Each dot corresponds to one onset. If a dot is above "0" on the y axis, the corresponding mallet strike took place after that of the leader, if a dot is below "0," the corresponding mallet strike took place before it. The right panel displays the spread of the phases. The good synchronizer **(bottom)** had very little spread relative to the poor synchronizer **(top)**. This spread was quantified using vector strength analysis (VS).

considered are highly correlated with each other, and 6 out of 9 of them are significantly correlated with *VS*.

As shown in **Table 2**, a significant correlation emerged from the ability to synchronize as assessed by *VS* and most of the other variables analyzed. *VS* was correlated with both SWAN categories, the percentage of correct responses in the congruent condition of the EFT, the RTV in both the congruent and incongruent conditions, and the reaction time difference between congruent and incongruent conditions.

The effects we observed were not driven by data from participants at the extreme end of the continuum of the SWAN-C rating, presenting the strongest ADHD-like behaviors. When data from the 20% of participants who scored most poorly on the SWAN-C scale is removed from the analysis, a similar pattern of correlations can be observed. These correlations are generally smaller (**Table 3**), but this can expected since the data is truncated (Edwards, 1984).

DISCUSSION

Results from our investigation of 102 children aged 7–12 indicate that better synchronizers are also more attentive (SWAN-I), show less ADHD-like behaviors (SWAN-C), and are more accurate with lower RTV on the EFT.

Consistent with these findings is the hypothesis by Rolf that early development of attention in children relies on synchronous social interaction that emerges from effective audio-visual integration (Rolf et al., 2009). Some theoretical work considers the ability of joint action as essential to effective social timing (Pacherie and Dokic, 2006). While such work primarily relies on an analysis of the role of the mirror neuron system in joint action, Schmidt et al. (2011) make the point in a recent article that "Even if perception and action coding occurs in mirror systems as argued by cognitive theorists and such a representational system is the mechanism that allows us to understand another's actions, we still need to understand how joint actions are coordinated in time." Our examination of the ability at rhythmic synchrony in a group context allows for experimental recording of precisely-timed conjoint action, while maintaining some ecological validity with respect to the classroom. Our finding of a significant correlation between rhythmic synchrony and attention behavior, as rated by teachers, provides an initial step toward establishing such an area of study.

The observed relationship between ability to synchronize and attention behavior may be explained in part by individual variability in the ability to generate rhythmic expectation. The capacity to synchronize is dependent upon the ability to generate

Table 2 | Correlation matrix.

	SWAN I	SWAN C	CONG	INC	RT CONG	RT INC	RTV CONG	RTV INC	RTD
VS	−0.41***	−0.42***	0.32**	0.15	−0.12	−0.057	−0.43***	−0.34**	0.22*
SWAN I		0.95***	−0.21	−0.13	0.084	0.0057	0.23*	0.18	−0.15
SWAN C			−0.19	−0.075	0.12	0.0085	0.27*	0.2	−0.22
CONG				0.81***	0.27*	0.34**	−0.41***	−0.62***	0.32**
INC					0.63***	0.6***	−0.057	−0.4***	0.13
RT CONG						0.94***	0.55***	0.23*	0.069
RT INC							0.47***	0.2	0.37***
RTV CONG								0.7***	−0.11
RTV INC									−0.075

It should be noted that bigger scores in the SWAN I and SWAN H scales are associated with poorer attention and higher hyperactivity respectively; both these variables are negatively correlated with the ability to synchronize. Higher variability in reaction time has also been associated with poorer attention. Individual correlations: $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

Table 3 | Correlation matrix in which data from participants with the poorest attention scores has been excluded from analysis.

	SWAN I	SWAN C	CONG	INC	RT CONG	RT INC	RTV CONG	RTV INC	RTD
VS	−0.35**	−0.38***	0.27*	0.14	−0.078	−0.031	−0.34**	−0.28*	0.16
SWAN I		0.92***	−0.2	−0.17	−0.04	−0.089	0.099	0.1	−0.079
SWAN C			−0.18	−0.094	0.028	−0.079	0.16	0.14	−0.19
CONG				0.81***	0.3*	0.36**	−0.37**	−0.62***	0.26*
INC					0.63***	0.59***	−0.042	−0.44***	0.031
RT CONG						0.92***	0.52***	0.15	−0.051
RT INC							0.46***	0.14	0.29*
RTV CONG								0.66***	−0.13
RTV INC									−0.11

*The procedure was identical to that of **Table 2** except that data from the 20% of children with the highest SWAN-C scores was excluded. Although the correlations are smaller, the same pattern as in **Table 2** can be observed. This indicates that the statistics are not dominated by the children at the end of the spectrum but can be seen throughout.*

expectation based on perceived patterns of temporal dynamics or rhythm, known as rhythmic expectation. The generation of rhythmic expectation enhances the ability of an individual to perform sensory discriminations at specific points in time. This aspect of attention, known as "dynamic attention" (Large and Jones, 1999), may play a role both in rhythmic performance and attentional behavior. Poor ability to generate rhythmic expectation can affect ability to modulate attention dynamically in accordance with temporal patterns created through joint action. This, in turn, could affect both ability to synchronize rhythmically and attention in interpersonal interaction.

In line with our findings showing a significant relationship between RTV and behavioral ratings of attention and also attention combined with hyperactivity-impulsivity (corresponding to attentional and combined diagnostic subtypes of ADHD, respectively), many studies have found increased RTV in those with ADHD on standard reaction time tasks [reviewed by Klein et al. (2006)]. Stimuli for such tasks are very frequently presented at a fixed interstimulus interval or ISI (e.g., continuous performance tests). Performance on such tasks, therefore, is partly dependent on the ability to synchronize because they require the generation of rhythmic expectations that enhance sensory discrimination at specific points in time, or when stimuli are presented (Large and Jones, 1999). The extensive literature on increased RTV in ADHD may then be attributable in part to impairment in the ability to synchronize.

Although the focus of this study is the relationship between rhythmic synchrony and *attentional* behavior, as measured by the inattentive components of the SWAN rating scale, we also found a significant correlation between rhythmic synchrony and *ADHD-like* behaviors as assessed by the combined (SWAN C) rating scale.

Much of the extant literature that examines the role of timing in relation to attention behavior focuses on differences between typically developing subjects and those with ADHD (Toplak et al., 2006). Such a focus tends to frame attention as a binary trait—something that a child either does or does not have. However, attentional behavior exists on a continuum, with the clinical population with ADHD occupying the extreme of the trait. We found that the significance of the correlation between the SWAN rating and VS holds across the full spectrum of attention behavior and rhythmic synchrony, even when the extremes of this continuum are eliminated from the analysis. This is important for our interpretation because it demonstrates that a relation between some aspects of temporal processing (and integration) and attention behavior is relevant to the entire population.

There are perhaps many subjacent deficits that can lead a child to exhibit behavior that teachers may perceive as associated with poor attention. It is important to understand what these subjacent deficits might be and identify behavioral biomarkers that can be associated with them. Based on our finding that the ability to synchronize in a group setting is correlated with teachers' perception of the attentional characteristics of a child, we pose that this ability can be one such biomarker. Further, this ability can be measured as it evolves in the context of a regular music class.

Synchronizing with others in a group music class context, aside from temporal processing and integration, also involves selective listening. Participants must be able to identify and focus on the target beat played by the leader. We attempted to minimize this by providing the teacher with an instrument that was significantly louder than, and had a very different timber than, the participants' instruments. In the future, it would be of interest to conduct a similar study that compares participants' synchrony in group and individual conditions and also includes a cognitive task for selective listening.

It could be argued that the observed correlation between rhythmic synchrony and SWAN ratings exists merely because, as with any cognitive task, those with poorer attention are less likely to be engaged. VS analysis (see Materials and methods) minimizes this effect because if a subject disengages completely (i.e., stops playing the instrument) the VS score remains unaffected, thus participants' synchrony was measured only when they were sufficiently engaged to be playing their instruments with the group. It should be stressed that we found that on all episodes the participants were performing the task, as shown by the fact that they were significantly synchronized.

Our study focused on attention in the classroom setting. Because our experimental design did not include measures of ability or achievement it is not known how the results obtained carry into those domains, although such comparisons will become important to our future work.

While the present study is one of numerous studies that have found a relationship between musical ability and other aspects of behavior (Forgeard et al., 2008; Kraus and Chandrasekaran, 2010), this study is unique in that it focuses on a specific—and quantifiable—component of musical performance: rhythmic synchrony. By measuring rhythmic synchrony directly, it is possible to find a continuum of individual differences in performance ability and correlate this continuum against other individual characteristics. Further, because music integrates multiple nested timescales, it is possible to extend the methodology we have developed to record participants individually in a group setting and measure their rhythmic synchrony to compare such things as sequence learning and synchrony, exploring multiple levels of synchrony across different timescales.

Although the idea that the practice of music positively influences general cognitive development appears entrenched in popular culture, there are few studies that have shown a causal relationship (Rauscher et al., 1997; Rauscher and Zupan, 2000; Schellenberg, 2004; Moreno et al., 2009). None of these intervention studies make clear what specific aspects of music practice might contribute to the observed changes. Parsing components of music practice (such as synchrony, sequencing, and pitch matching) in such a way that their role in possible cognitive changes can be measured will be an important step both for scientific study of music and for the development of specific music programs. This study is correlational and cannot test whether a causal relationship exists between music and attention. However, causation cannot exist without correlation and thus establishing the existence of a correlation with a specific and measurable component of music practice is a necessary step toward investigating causation before entering into complex and costly intervention studies.

The key finding of this study is the significant correlation between rhythmic synchrony and attention behavior. Many studies have investigated correlations between the practice

of music and various elements of cognition (Kraus and Chandrasekaran, 2010). The present study, however, rather than investigating music practice in general, quantifies a specific component of music: rhythmic synchrony. We hope that this study and its methodology will point toward further quantifiable investigation of relationships between music and cognition.

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High school music classes enhance the neural processing of speech

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Should music be a priority in public education? One argument for teaching music in school is that private music instruction relates to enhanced language abilities and neural function. However, the directionality of this relationship is unclear and it is unknown whether school-based music training can produce these enhancements. Here we show that 2 years of group music classes in high school enhance the neural encoding of speech. To tease apart the relationships between music and neural function, we tested high school students participating in either music or fitness-based training. These groups were matched at the onset of training on neural timing, reading ability, and IQ. Auditory brainstem responses were collected to a synthesized speech sound presented in background noise. After 2 years of training, the neural responses of the music training group were earlier than at pre-training, while the neural timing of students in the fitness training group was unchanged. These results represent the strongest evidence to date that in-school music education can cause enhanced speech encoding. The neural benefits of musical training are, therefore, not limited to expensive private instruction early in childhood but can be elicited by cost-effective group instruction during adolescence.

Keywords: hearing, training, music, brainstem, auditory perception

INTRODUCTION

The role of music education in schools is under debate, as music competes with other in-school programs for access to a small pool of funding. At the center of the debate is the question of whether in-school music education bolsters the development of the brain and mind. It has been hypothesized that music can function as a training ground for language skills (Patel, 2011) as a result of its acoustic and structural overlap with language and its tendency to capture attention and emotion (Menon and Levitin, 2005). In support of this hypothesis, private, one-on-one music instruction improves language abilities including verbal memory (Chan et al., 1998), literacy (Tallal and Gaab, 2006; Moreno et al., 2009), verbal intelligence (Forgeard et al., 2008; Moreno et al., 2011), and speech processing (Kolinsky et al., 2009; François et al., 2012). Across the lifespan, highly trained musicians also display an impressive advantage for perceiving speech in background noise relative to their musically naive counterparts (Parbery-Clark et al., 2009b, 2011; Strait et al., 2012; Zendel and Alain, 2012). Linked to this behavioral advantage is a greater neural resilience to background

noise and other forms of acoustic degradations (Bidelman and Krishnan, 2010). Noise delays the neural response to sound (Burkard and Sims, 2002); however, faster neural responses to degraded speech are consistently linked to music training (Parbery-Clark et al., 2009a; Kraus and Chandrasekaran, 2010; Strait et al., 2012), enhanced speech-in-noise perception (Parbery-Clark et al., 2009a), and better reading abilities (Anderson et al., 2010) across the lifespan (see Kraus and Chandrasekaran, 2010; Strait and Kraus, 2013 for reviews).

There is converging evidence, therefore, that music training can improve neural encoding of speech. An alternate explanation, however, is that musicians have inherently advanced auditory skills and are thus drawn to musical training. Longitudinal work investigating both a musical training and a control training group can conclusively show that musical training produces speech encoding benefits and rule out pre-existing differences in neural function. Longitudinal studies have revealed that music training can lead to enhanced auditory neural function (Fujioka et al., 2006; Shahin et al., 2008; Moreno et al., 2009; Chobert et al., 2012; François et al.,

2012; Strait et al., 2013). However, the training used in these studies was either computerized or one-on-one music lessons, and it is unclear whether group music lessons within a school setting yield similar outcomes. The investigation of the neural effects of in-school music training, therefore, is crucial for providing empirical evidence relevant to the debate about the efficacy of music education in schools. Our study was unique in that it accessed adolescents undergoing group music classes within a public school setting.

Our study was further motivated by the fact that public music education is on the decline (National Endowment for the Arts survey, Rabkin and Hedberg, 2011) and that private music lessons, due to their expense, are more accessible to socioeconomically advantaged, relative to disadvantaged, families (Duke et al., 1997). By partnering with schools that offer music education to low-income minority communities, we hoped to understand the extent to which in-school musical training might benefit a population that otherwise might not have access to music education.

Using a longitudinal design, we investigated how in-school music training affects the adolescent brain by studying high school students from the Chicago Public School district. As students from a district serving largely socioeconomically disadvantaged families, these subjects represent a population that has been understudied by biological scientists. Participants were tested prior to and immediately following 2 years of training. We hypothesized that classroom musical instruction increases the brain's resilience to background noise and we, therefore, predicted that after training, music students would have earlier neural responses to speech presented in noise. Electrophysiological responses were measured to a synthesized speech syllable presented repetitively in the presence of background noise (six-talker babble; **Figure 1**; Skoe and Kraus, 2010). Analyses focused on the neural response to the dynamically changing portion of the syllable (10–70 ms), as earlier timing within this response region has been linked with musical training (Parbery-Clark et al., 2012).

MATERIALS AND METHODS

PARTICIPANT AND GROUP CHARACTERISTICS

Subjects were 43 adolescents attending three public high schools in Chicago [music training $n = 21$ (11 female), fitness training $n = 22$ (7 female, sex difference: $p > 0.15$, chi-square = 1.87)]. 14 students participated in the study at pre-test but were unable to come back for the post-testing phase. Four of these students dropped out of the study voluntarily and 10 were unable to return for personal reasons (school transfers, family emergencies, medical conditions, etc.) Mean age at pretest was 14.6 years (standard deviation 0.46) for the music training group and 14.7 (0.34) for the fitness training group. This age difference was not significant according to an independent t-test, $t(41) = 0.49$, $p > 0.5$. As part of the curriculum for each of these schools, all students must enroll (for credit) in either music or Junior Reserve Officer's Training Corp (JROTC) classes which meet 2–3 times each week, averaging about 3 h of instruction each week. Music students participated in either band ($n = 9$) or choral ($n = 12$) class.

Students were tested prior to beginning music or fitness classes, providing a baseline measure of neural function. This
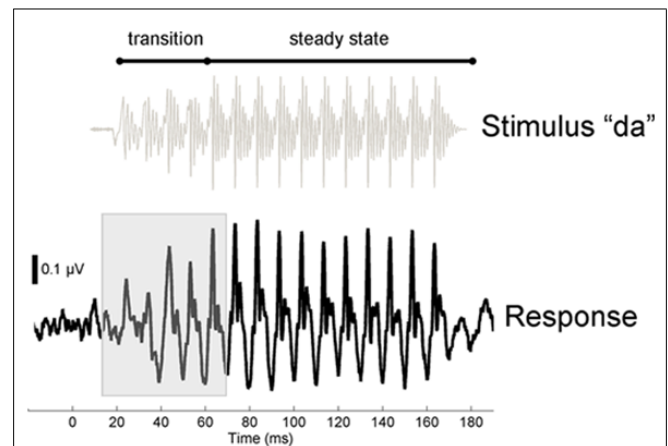

FIGURE 1 | Stimulus and response time-domain waveforms. To illustrate the temporal characteristics of the stimulus and auditory brainstem response, the baseline grand average response (average of trained and control group) is plotted below the waveform for the stimulus [da], which was presented in a noisy background of multi-talker babble. The speech stimulus is divided acoustically into a transition region, during which the speech formants change linearly as the sound moves from the consonant to the vowel, and a steady-state vocalic portion of the stimulus, where the spectrotemporal profile of the stimulus is stable. Compared to the steady-state region, the formant transition region is more strongly masked by the presence of noise. The response to the spectrotemporally dynamic transition is highlighted (10–70 ms). We compared the stimulus and the response by calculating the time lag, for each subject, at which the two waveforms align more closely. For the grand average waveform plotted here, the maximum correlation is achieved at a lag of 7.9 ms. Consequently, for this graph the stimulus waveform was shifted by 7.9 ms to the right to maximize the visual alignment with the response.

baseline measure was critical in establishing that differences in brain function following 2 years of training are linked to training and not confounded by initial group differences. While no subjects in the fitness training group had any prior musical training, two subjects in the musical training group had a small amount of formal musical training for 1 and 6 years. However, given that the two groups were matched on neural timing at pre-test, we interpret any differences in year-to-year changes in neural timing to the different training regimens that the two groups received during the study. Groups were matched on pre-training performance using measures of IQ (Wechsler Abbreviated Scale of Intelligence, WASI; musicians: 99.57 ± 11.57; ROTC: 98.23 ± 7.45; $F = 0.207$, $p = 0.651$), reading abilities (Word Attack, Woodcock-Johnson III test battery; musicians: 97.62 ± 9.68; ROTC: 101.68 ± 11.76; $F = 1.521$, $p = 0.225$), and auditory working memory (Auditory Working Memory, Woodcock-Johnson III test battery; musicians: 103.71 ± 11.03; ROTC: 103.64 ± 10.46; $F = 0.001$, $p = 0.981$). Groups were matched on SES using maternal education as an index of SES (Hackman et al., 2010; Kolmogorov–Smirnov $z = 0.986$, $p = 0.285$). Both groups were from predominately low SES backgrounds, with the majority of subjects reporting a maternal education level of high school graduate. Additional inclusionary criteria were normal hearing as determined by air conduction thresholds (<20 dB normal hearing level for octaves from 125 to 8000 Hz), click-evoked brainstem response latencies within normal limits (5.41–5.97 ms; the 100-μs

rarefaction click stimulus was presented at 80 dB sound pressure level (SPL) at a rate of 31/s), and no external diagnosis of a reading disorder.

DESCRIPTION OF MUSIC CURRICULUM

The curriculum is designed as a 4 year sequence that takes incoming students at a beginning level and prepares them to participate in college-level music classes. Band and choir curricula are developed in tandem so that students in either track graduate from high school with a similar level of musical skill. Singers receive additional keyboard training. Students participate in a minimum of two public performances per year. Lessons include practice in sight reading, singing/playing technique, and regular assessments to measure student progress. Assessments include written exams related to music theory, singing/playing exams that address continuous growth as well as concert readiness, and content-based writing assignments.

DESCRIPTION OF FITNESS CURRICULUM

This curriculum is also designed as a 4 year sequence. Its primary focus is to develop leadership skills, strengthen character, and instill self-discipline through classroom instruction and fitness training. Students are graded and promoted based on demonstrating knowledge and mastery of the concepts covered in the classroom as well as achieving muscular and cardiovascular fitness milestones.

STIMULUS AND RECORDING

Stimulus and recording parameters followed those described in Skoe and Kraus (2010). The stimulus was the synthesized speech syllable [da], a six-formant, 170 ms sound characterized by an initial stop burst followed by a 40 ms voiced formant transition. The transition is followed by a 120 ms steady-state [a] vowel in which the formants are unchanging. The [da] stimulus was presented in alternating stimulus polarities at a rate of 3.98/s to the right ear at 80 dB SPL through an insert earphone (ER-3; Etymotic Research) using the stimulus presentation software NeuroScan Stim2 (Compumedics). Ag/Ag-Cl electrodes were applied in a vertical montage from Cz to right earlobe with forehead as ground. Responses were recorded in a sound-attenuated, electrically shielded chamber using NeuroScan Acquire 4 at a 20 kHz analog-to-digital sampling rate. To keep the participant still but awake during electrophysiological testing, the participant watched a movie of his or her choice in a comfortable reclining chair. The left ear remained unoccluded during the recording session so that the movie soundtrack was audible. The stimulus was presented in the context of multi-talker background babble. The stimulus was presented at a signal-to-noise ratio of −10 dB relative to the root mean square amplitude of the background noise.

Although normal language processing generally involves the use of attention, it also relies upon other, automatic processes. The ability to consciously perceive the meaning of speech presented in noise, for example, depends upon the ability to accurately, efficiently, and precisely represent acoustic characteristics of sound. The automatic representation of the basic characteristics of sound can be captured in the auditory brainstem response, which can be elicited when a subject is performing a task unrelated to the target

stimulus or is asleep (Skoe and Kraus, 2010). Despite the passive nature of the recording paradigm, characteristics of the auditory brainstem response such as the strength of spectral encoding and the timing of identifiable peaks in the waveform have been linked to abilities such as reading (Anderson et al., 2010), speech in noise perception (Kraus and Chandrasekaran, 2010), and consonant-vowel syllable discrimination in noise (de Boer et al., 2012). The fact that the auditory brainstem response can be elicited even if attention is not directed to the target stimulus is a major strength of the methodology, allowing researchers to assess auditory encoding with a technique relatively unaffected by transient changes in cognitive or emotional state. As a result, the auditory brainstem response has a high degree of test-retest reliability (Russo et al., 2004; Song et al., 2011), providing a stable snapshot of an individual's auditory encoding. Another important characteristic is that, due to temporal precision of subcortical nuclei and their ability to phase-lock to relatively high frequencies (up to 1,000 Hz; Liu et al., 2006), the response mirrors many of the acoustic characteristics of the evoking stimulus (Galbraith et al., 1995). In contrast, the cortical response can only phase-lock up to frequencies of roughly 100 Hz (Steinschneider et al., 2008), and as a result cortical responses do not actively reproduce spectrotemporal content in the frequency range of speech formants.

Electrophysiological responses were bandpass filtered offline in Neuroscan Edit (Compumedics) from 70 to 2000 Hz (12 dB/octave, zero phase-shift) to include energy within the phase-locking limits of the midbrain (Liu et al., 2006) and to minimize low-frequency cortical activity. Responses were pre-stimulus baseline corrected and epoched over a −40 to 190 ms window, with stimulus onset occurring at time 0. An artifact reject criterion of ±35 µV was applied. A final added response representing 6000 trials, 3000 from each stimulus polarity, resulted for each subject.

DATA ANALYSES

To investigate timing shifts between pre- and post-training, we employed two methods: stimulus-to-response correlation (Skoe and Kraus, 2010) and the cross-phaseogram. Responses at pre- and post-training sessions were compared to the original stimulus by identifying the shift that was necessary to maximize the cross-correlation between the response to the stimulus, with this shift limited to values between 7 and 14 ms. This procedure identifies the neural transmission delay (or "lag") between presentation of a stimulus and the neural response.

The cross-phaseogram (Skoe et al., 2011) is an objective measure of timing that relates strongly to timing shifts of response peaks (Tierney et al., 2011). A cross-phaseogram was constructed for each subject, using custom routines coded in MATLAB (The MathWorks Inc.): phase shifts were calculated on 40 ms overlapping windows of the response; the midpoint of the first window started at 10 ms, with each subsequent window shifted by 1 ms, and the final window centered on 70 ms. First, each of these windows was baseline-corrected, then ramped on and off using a Hanning window. Next, the cross-frequency spectrum of each window was calculated and converted to phase angles using the cross-power spectral density function. Jumps between successive blocks of greater than π were corrected to

their 2π complement. The resulting cross-phaseogram plot is a three-dimensional (3D) image, with the degree of shift mapped to different values on the red-green-blue color spectrum. Regions colored in green indicate that there was no effect of training on the phase of responses. For regions appearing red, the response at post-training was earlier relative to responses to pre-training; for regions colored in blue, responses post-training were later than responses to (da) pre-training. Average phase shifts over 70–400 Hz during the 10–70 ms dynamically changing portion of the response were analyzed between groups. This frequency band was previously shown to be important in identifying differences in encoding (da) presented in quiet and noise (Tierney et al., 2011).

RESULTS

Neural response timing was analyzed using two converging methods. First, we measured the lag between the stimulus and response using cross-correlation (Skoe and Kraus, 2010), with a greater lag in neural response timing reflecting greater neural delays (**Figure 2**). Using a repeated measures ANOVA with testing year as the within-subject factor and training group as the between-subject factor, we found a significant interaction between year and training group $[F(1,41) = 6.39, p = 0.015]$, but no main effects [Training group: $F(1,41) = 0.155, p = 0.696$; Year: $F(1,41) = 0.553$, $p = 0.461$]. One-tailed *post hoc* paired t-tests revealed that between years, stimulus-response lag decreased for the musically trained group [shift = -0.25 (0.56) ms; t-stat = 2.03, $p = 0.028$] but not the fitness-trained group [shift = 0.14 (0.43) ms; t-stat = -1.48, $p = 0.923$]. The two groups were matched on stimulus-response lag in year 1 (t-stat = 1.19, $p = 0.239$), confirming that the different effects of training were not driven by pre-existing differences in neural timing. See **Figure 3** for a depiction of average waveforms in the two training groups at pre-test and post-test.

To confirm the effect of musical training, we computed phase shifts between responses collected before and after 2 years of training (**Figure 4**). This method generates a measure of timing shift between two recordings that correlates with shifts in manually

FIGURE 2 | In-school music training increases neural resilience to the effects of noise. After 2 years, the stimulus-to-response lag was earlier for the musically trained group (red) while the fitness-trained group (black) did not change from pre-test. Stimulus-to-response lag was computed automatically using a cross-correlation algorithm. Error bars represent ±1 standard error of the mean.

marked peak latencies (Tierney et al., 2011). Following training, musician responses were earlier [-0.20 (0.40) radians], while the response of the fitness-trained participants remained unchanged [0.11 (0.42) radians]. These two shifts were significantly different (t-stat = 2.51, $p = 0.0016$). One-tailed t-tests revealed that the music group's shift (t-stat = 2.34, $p = 0.0149$), but not the fitness group's shift (t-stat = 1.24, $p = 0.887$) was significantly smaller than zero, indicating that enhancements in the timing of neural responses to noisy speech were exclusive to music training.

DISCUSSION

Here we show that high school music instruction enhances the neural representation of speech in background noise, a neural advantage previously found to result from more extensive one-on-one training. Moreover, our subjects live in relatively low-income areas and reported relatively low levels of socioeconomic status (SES). Given that SES impacts language functioning (Hackman et al., 2010) and the neural encoding of speech (Skoe et al., 2013), our results suggest that affordable in-class musical training may be able to ameliorate some of the negative consequences of impoverishment.

Some musician advantages are larger if training is begun earlier in life (Penhune, 2011), and so the effects of in-class music training may be even larger in younger populations. Nevertheless, we find that 2 years of in-class training in adolescence can enhance how the brain encodes speech. Though neural plasticity has declined somewhat by the time a child reaches adolescence, the window for successful training-based intervention remains open. As computer-based training can enhance sensory processing even in older adult subjects (Mahncke et al., 2007; Berry et al., 2010; Anderson et al., 2013), it may never be too late to benefit from newly acquired experience such as music instruction.

Much of the research on musical training's effects on the brain has compared subjects with many years of extensive musical training to those without. These group differences are then assumed to result from musical experience. However, it is possible that individuals with superior auditory abilities are more strongly drawn to music as a hobby or career. Although correlations between extent of musical experience and neural function (Parbery-Clark et al., 2009a; Strait et al., 2012; reviewed in Strait and Kraus, 2013) support training-dependent plasticity, it remains possible that subjects with certain characteristics, whether environmental or genetic, are more likely to continue their training rather than abandoning it. Here, by using a longitudinal approach to examine neural changes in students who were matched in reading, IQ, and neural function before training began, we present the strongest evidence to date for a causative role of in-school musical training in modulating the neural encoding of speech.

In the musically-trained group, the neural responses were found to be 0.25 ms earlier after two years of training. Although 0.25 ms is a small difference in latency compared to the duration of a word or a sentence, auditory brainstem response latency differences of as little as 0.2 ms are clinically significant. For example, small differences in the timing of brainstem responses elicited by presentation to each ear can be used to diagnose
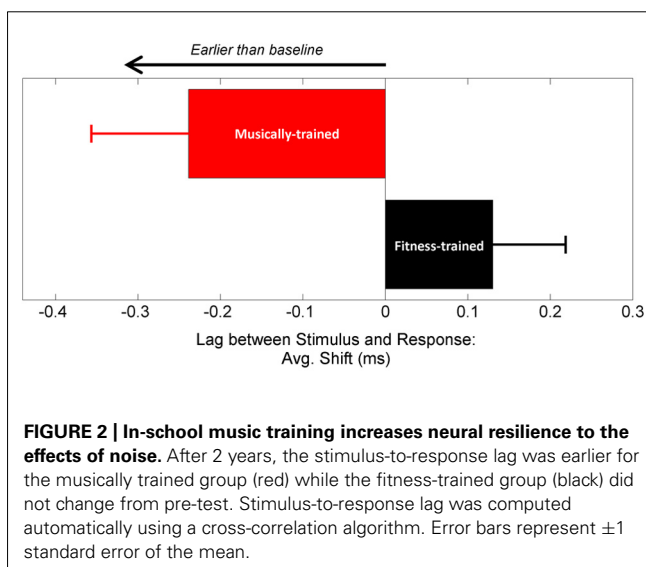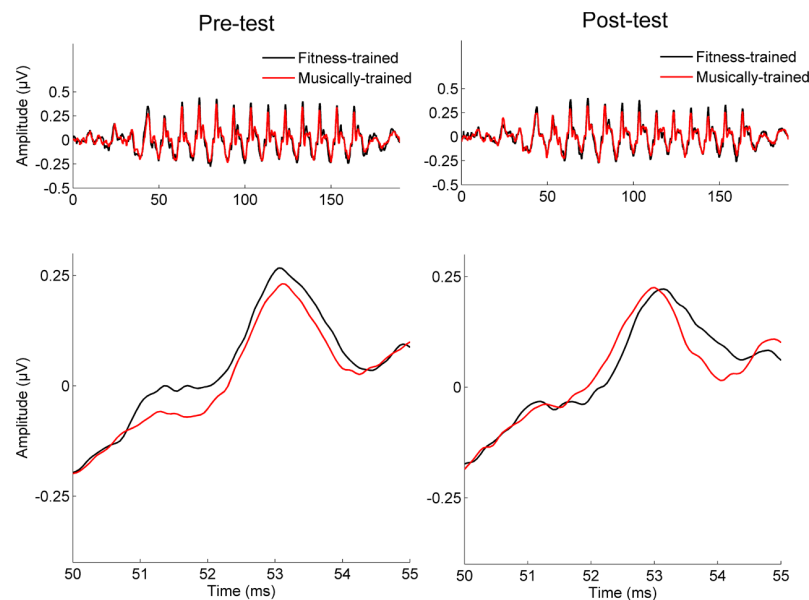
FIGURE 3 | Pre-test and post-test waveforms in musically trained and fitness-trained groups. Grand average neural responses for the musically trained (red) and fitness-trained (black) groups at pre-test and post-test, displayed across the entire subcortical response (top) and at a single response peak (bottom).
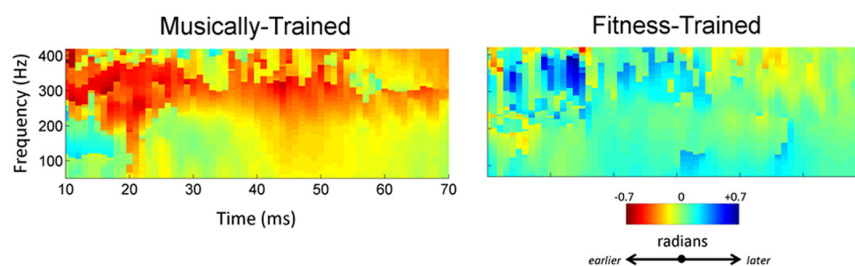

FIGURE 4 | High school music classes lead to earlier brain responses to speech. Following training, the music group (left) shows an earlier response as evidenced by a negative phase-shift within the 70–400 Hz range that appears as a band of red. The neural response of the fitness training group (right) was stable (green) from pre- to post-test.

the presence of tumors of the vestibulocochlear nerve (Grayeli et al., 2008). The consistent associations found between auditory brainstem latency and language skills such as speech-in-noise perception (Kraus and Chandrasekaran, 2010), reading (Anderson et al., 2010), and consonant-vowel discrimination in noise (de Boer et al., 2012) suggest that early brainstem timing is crucial for auditory processing. Moreover, the reversal of age-induced delays in neural timing by auditory training (Anderson et al., 2013) suggests that earlier neural timing is advantageous. The exact mechanisms by which auditory brainstem latency influences auditory processing, however, remain a subject for future research. The enhancements reported here, therefore, suggest that our musically trained participants benefit from improved speech in noise perception and reading abilities. Classrooms are not ideal acoustic environments for instruction: background noise commonly exceeds recommended levels (Knecht et al., 2002) and higher levels of background noise are linked to worse performance on standardized tests (Shield and Dockrell, 2008). Perception of

speech in noise, therefore, may be vital for a child's ability to understand what is being communicated in classrooms. Therefore, our finding of an enhancement of the neural encoding of speech in noise, along with previously reported cognitive benefits of long-term musical training (reviewed in Strait and Kraus, 2013), suggest that musical training may be able to improve academic performance by training perceptual and cognitive skills (such as auditory working memory, reading, and speech in noise perception) on which scholastic ability depends. Future work should examine the effects of music classes on scholastic measures such as standardized tests or grades and investigate whether any academic enhancements due to music training can be attributed to increased perceptual or cognitive skills. As a result, we suggest that, when considering the role of music education in school, its potential linguistic, cognitive, and scholastic benefits should be factored in alongside its more obvious esthetic benefits. Future work should investigate how these neural changes translate to academic benefits, as well as whether training-induced enhancements persist

after instruction ceases (Skoe and Kraus, 2012; White-Schwoch et al., 2013). Another important direction for future work concerns the delineation of the different sub-components of musical training responsible for certain neural enhancements. For example, music reading, ear training, group synchronization, and solo practice may all have different effects on the developing brain. Yet another potentially fruitful direction for future research is in identifying functional and structural features of the brain that predict the ability to benefit from music education (Zatorre, 2013).

It remains an open question how the benefits of music training for auditory neural encoding compare to more language-directed computer-based auditory training or one-on-one speech therapy. Benefits for speech-in-noise processing may be achievable through other means besides music. In practice, however, it is difficult to ensure steady engagement with an auditory training program for extended periods of time, because waning motivation leads to decreased participant compliance and because such programs are often not designed to be used for lengthy periods. Music's inherently rewarding and emotionally evocative nature (Patel, 2011; Salimpoor et al., 2013), on the other hand, make it a uniquely sustaining way to train auditory skills.

One-on-one speech therapy could be a more feasible way to train speech listening skills for a sustained period of time, as the personal interaction included as part of the therapy would likely be more engaging for the participant, leading to greater long-term compliance. Speech therapy is comparatively expensive, however, requiring the personal attention of a trained therapist, while the enhancements that we demonstrate are the result of classroom-based music training. Future work should directly test the comparative value provided by in-school music training versus speech therapy in terms of benefits versus costs. Furthermore, both speech therapy and computer-based auditory training remove children from the classroom, while music classes take place within the school curriculum as part of the regular school day. Future work should directly test the comparative value provided by in-school music training versus speech therapy in terms of benefits versus costs. The benefits of music training also extend beyond speech processing, encompassing cognitive benefits such as auditory attention and working memory (reviewed in Kraus et al., 2012). Ultimately, music training and speech therapy are not mutually exclusive options; the largest benefit would likely be gained by students who engage in both kids of training.

In summary, in-school group training during adolescence can enhance the brain's processing of speech in noise. As such, the enhancement of speech encoding by musical experience may not require the development of expert musical skills, and is accessible regardless of age or income. This study is consistent with the notion that music is an important part of a well-rounded school curriculum, alongside foreign language instruction, math, reading, and other elements vital for a child's development.

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frontiers in PSYCHOLOGY

The genetics of reading disabilities: from phenotypes to candidate genes

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This article provides an overview of (a) issues in definition and diagnosis of specific reading disabilities at the behavioral level that may occur in different constellations of developmental and phenotypic profiles (patterns); (b) rapidly expanding research on genetic heterogeneity and gene candidates for dyslexia and other reading disabilities; (c) emerging research on gene-brain relationships; and (d) current understanding of epigenetic mechanisms whereby environmental events may alter behavioral expression of genetic variations. A glossary of genetic terms (denoted by bold font) is provided for readers not familiar with the technical terms.

Keywords: dyslexia, attention deficit/hyperactivity disorder, language impairment, speech sound disorder, genetics, candidate genes, reading impairment, brain imaging

COMPLEX PHENOTYPE OF SPECIFIC READING DISABILITIES

Specific reading disabilities are genetically and phenotypically **complex** neurobehavioral disorders that affect 5–10% of school-aged children, depending on criteria used to make the diagnosis (Shaywitz et al., 1990b; Katusic et al., 2001). Although anyone with a developmental disability is likely to have difficulty learning to read, specific reading disability is reserved for those whose overall developmental falls at least within the lower limits of the normal range and thus the reading problem cannot be attributed to the developmental disability. Some specific reading disabilities are associated with difficulty decoding unfamiliar words and/or difficulty in recognizing real words encountered before. To assess decoding, pseudowords or non-words that can be pronounced by applying alphabetic principle but are not associated with a conventional meaning are used, whereas to assess real word reading, written words that are associated with one or more conventional meanings are used.

More research has been conducted with dyslexia than other kinds of specific reading disabilities. According to the International Dyslexia Association (Lyon et al., 2003) dyslexia is characterized by a struggle in acquiring written language at the word level, showing deficits in accurate and/or fluent word recognition, decoding, and spelling. Secondary effects on comprehension and reduced reading experience may result, which, in turn, can lead to impoverished vocabulary and the general knowledge base.

A phonological processing deficit, interpreted as evidence of disordered internal representation of speech sounds, is often associated with dyslexia. For example, dissecting words into individual sounds and making changes to their sequence is difficult for individuals with dyslexia, compared to individuals without dyslexia (Morais et al., 1986; Fletcher et al., 1994; Anthony et al., 2002). Phonological short-term memory may be impaired as well, which is assessed with non-word imitation tasks, where non-words such as "woodoip" or "bamadana" are presented as targets to be repeated (Wagner et al., 1999). Naming (producing spoken names) for visual stimuli (e.g., colors, objects, letters, numerals) rapidly (Rapid Automatic Naming, RAN) is also frequently impaired in individuals with dyslexia (Wolf and Bowers, 1999). For instance, children with dyslexia were slower and less accurate than children without dyslexia in RAN for pictures (Denckla and Rudel, 1976; Catts, 1986; Wolf and Bowers, 1999). Whereas in the past, deficits in phonological processing ability were thought to be caused by deficits in auditory perception, especially when rapid acoustic transitions were involved (Tallal, 1980; Farmer and Klein, 1993), more recent research shows that extraction of linguistic units larger than phonemes, e.g., syllables and words, from the speech stream may also be deficient in individuals with specific reading disabilities (Johnson et al., 2011) who may process other acoustic features such as cues for voice identification less efficiently (Perrachione et al., 2011).

Processes beyond those involving speech sounds appear to be implicated. Evidence has accumulated that working memory (Swanson and Berninger, 1995; Swanson and Siegel, 2001) and central executive functions (Lyon and Kranegor, 1996; Swanson, 2000; Berninger et al., 2006) in working memory are impaired in reading disabilities in general and dyslexia in particular. Children with oral language impairment (LI; Miller et al., 2001; Leonard et al., 2007) and written LIs including dyslexia (Catts et al., 2002b;

Smith et al., 2008; Peter et al., 2011a) may also have slowed processing speeds. Many studies have found an excess of males, with male:female ratios typically ranging from 1:5 to 3:1 in reading disability (Flannery et al., 2000; Katusic et al., 2001; Rutter et al., 2004), but more recently several studies have shown that the gender difference may be specific to the impaired spelling and related writing skills in dyslexia, not the reading skills (for review, see Berninger et al., 2008). Ascertainment bias may account for a portion of this sex differential (Shaywitz et al., 1990a). With appropriate educational intervention, most affected individuals eventually achieve some proficiency in reading and writing skills, but deficits in phonological decoding, fluent oral reading, and spelling often persist into adulthood even in those whose word reading problems appear to be "compensated" (Bruck, 1990, 1992, 1993; Pennington et al., 1990; Wilson and Lesaux, 2001; Berninger et al., 2006).

Several factors complicate studies of the etiology of reading disabilities in general and dyslexia in particular. First, problems with reading are not limited to dyslexia. Other developmental disabilities, such as LI and speech sound disorder (SSD), share reading impairment (Catts et al., 2002a, 2008; Peterson et al., 2009; Landerl and Moll, 2010), and study populations may contain mixtures of individuals with different underlying disorders. Second, reading disability may co-occur with these other disorders or with attention deficit disorder, all of which also have a genetic basis (Pennington and Bishop, 2009), and such comorbidity may confound the parsing of etiologies. Third, because the distributions of reading ability relative to age or IQ are continuous, the setting of a discrete threshold for dyslexia is somewhat arbitrary and varies among different research groups.

One emerging approach to dealing with this lack of homogeneity regarding kinds of reading disabilities is to differentiate between developmental disabilities, specific learning disabilities, and **endophenotypes**. For example, in a special issue devoted to improving communication and collaboration among speech and language specialists, psychologists, and educators, a model was proposed for defining and diagnosing disabilities based on profiles (patterns of variables or constellations) rather than a single variable out of context of other related, relevant variables (Silliman and Berninger, 2011). Evidence exists for five domains of development (each related to different brain systems): (a) cognition and memory; (b) receptive and expressive language; (c) sensory and motor systems; (d) social and emotional systems; and (e) attention and executive function systems. Individuals who fall outside the normal range in one or more but not all developmental domains have specific developmental disabilities (SDDs) and those who fall outside the normal range in all developmental domains have pervasive developmental disabilities (PDDs). Sometimes diagnosed PDDs or SDDs are associated with specific neurogenetic disorders with characteristic phenotypes, for example, fragile X or Williams syndrome (Batshaw et al., 2007). For students without SDDs or PDDs, behavioral profiles are assessed for specific aural language skills (language by ear), specific oral language skills (language by mouth), specific reading skills (language by eye), and specific writing skills (language by hand; Liberman, 1999; Silliman and Berninger, 2011), each of which has different levels of language (subword, word, and text) that should be differentiated

from speech sound processing and production/articulation disorders (Berninger and Niedo, 2012). Evidence is accumulating that three kinds of specific written language disabilities – dysgraphia (impaired handwriting), dyslexia (impaired word decoding and spelling), and selective language disorder (oral and written language learning disability, OWL LD) can be identified and differentiated on the basis of which working memory component/s is/are impaired (spoken and written word form and syntactic storage and processing units; phonological and orthographic loops; and supervisory attention/executive functions like selective attention, switching attention, and sustained attention). Each working memory component could be associated with different genetic etiologies (Berninger and Richards, 2010).

Given this potential confounding of impaired reading found in many kinds of developmental and learning disabilities, it is often difficult to determine whether samples across different genetic studies include the same kinds of reading disabilities or patterns of impairments in individuals with reading disabilities. Nevertheless, the evidence to date on impaired reading (word decoding, word recognition, and reading comprehension) and writing is yielding new knowledge about the biological basis of developmental and learning disabilities. As progress is also made toward a closer description of the various observable traits at the behavioral level, the relationships between various candidate genes, whether acting alone or together, and observable forms of reading disorders may become clearer.

GENETIC INFLUENCES ON SPECIFIC LEARNING DISABILITIES
GENETIC BASIS OF READING DISABILITIES
In the context of this overview, it is important to keep in mind that reading disability and dyslexia are often used interchangeably and samples may include reading disabilities related to a variety of language and speech impairments. Genetic influences on reading ability have been demonstrated (Gilger et al., 1994; Reynolds et al., 1996; Harlaar et al., 2005; Davis et al., 2009; Lind et al., 2010) and multiple lines of evidence have led to the consensus that reading impairment has a genetic basis. The earliest observations of **familial clustering** and increased **recurrence risk** of dyslexia in relatives date from the early 1900s (Hinshelwood, 1907; Stephenson, 1907; Hallgren, 1950; DeFries et al., 1978). Twin and adoption studies showed that the familial clustering reflects shared genetic factors more than shared environment (DeFries et al., 1987; Stevenson et al., 1987; Pennington et al., 1991; Gayán and Olson, 2001, 2003; Wadsworth et al., 2002). Most **heritability** estimates range from 40 to 60%. Dyslexia and some component **phenotypes** aggregate in families in a manner consistent with a genetic etiology (Raskind et al., 2000; Hsu et al., 2002) and allow **models of transmission** to be fit (Pennington et al., 1991; Wijsman et al., 2000; Chapman et al., 2003).

GENETIC HETEROGENEITY
Although the heritability of a specific reading disability such as dyslexia has been shown to be high, it is clear that dyslexia is a genetically **heterogeneous** disorder, and for most individuals it is highly likely that more than one genetic factor interact to cause the susceptibility. By both **targeted** and **genome-wide** studies, more than 20 genes and locations have been associated

with dyslexia, including nine that have been designated dyslexia loci DYX1–9 by the Human Gene Nomenclature Committee www.genenames.org/. Similar studies have identified candidate locations for genes that modulate LI and other related disabilities (Barry et al., 2007; Conti-Ramsden et al., 2007; Hayiou-Thomas, 2008; Newbury and Monaco, 2010; Newbury et al., 2010; Willcutt et al., 2010). Furthermore, there is evidence for overlapping genetic risk factors among speech disorders, LI, and reading disability (Caylak, 2007; Pennington and Bishop, 2009; Newbury et al., 2011), which may be best understood in the context of shared risks and unique contributors that lead to the specific behavioral profile. We provide a synopsis of these putative genetic loci.

To date, eleven genome-wide scans for dyslexia (Fagerheim et al., 1999; Nopola-Hemmi et al., 2001; Fisher et al., 2002a; Kaminen et al., 2003; de Kovel et al., 2004; Raskind et al., 2005; Igo et al., 2006; Brkanac et al., 2008; König et al., 2011; Rubenstein et al., 2011; Svensson et al., 2011) and genome-wide association scans for early reading disability (Meaburn et al., 2008) and an electrophysiologic measure related to speech processing (Roeske et al., 2011) have been reported. Not all studies have obtained significant results (Meaburn et al., 2008; Svensson et al., 2011).

The DYX1 locus on chromosome 15 (**MIM** 127700) was first proposed by Smith et al. (1983) in a study of nine multigenerational families in which a **centromeric cytogenetic heteromorphism** appeared linked to dyslexia defined categorically. When the study was extended the **logarithm of odds** (**LOD**) score decreased (Fain et al., 1985; Lubs et al., 1991) and an independent study failed to detect **linkage** to this location even though it included a large family that had provided almost all the original chromosome 15 signal (Rabin et al., 1993). However, by targeted analyses of chromosome 15q as well as genome-wide approaches, multiple groups obtained evidence for a locus more **distal** on the **long arm** (q21) for single word reading and spelling (Grigorenko et al., 1997, 2007; Schulte-Korne et al., 1998; Nöthen et al., 1999; Morris et al., 2000; Chapman et al., 2004; Marino et al., 2004; Bates et al., 2007; Schumacher et al., 2008; Rubenstein et al., 2011).

Evidence for a locus on chromosome 6p (DYX2) was originally reported by Cardon et al. (1994, 1995). They targeted the **HLA locus** based on a hypothesis about a relationship between autoimmunity and dyslexia. Since that time, the DYX2 locus on 6p21 (OMIM 600202) has been intensively studied using multiple phenotypes, both categorically defined or modeled as continuous variables, and linkage has been replicated by multiple groups (Grigorenko et al., 1997, 2007; Fisher et al., 1999; Gayan et al., 1999; Petryshen et al., 2000; Kaplan et al., 2002; Marlow et al., 2003; Turic et al., 2003; Deffenbacher et al., 2004; Cope et al., 2005a; Schumacher et al., 2006a). As observed for DYX1, linkage, and **association** studies between dyslexia and DYX2 have not provided uniformly supportive results (Field and Kaplan, 1998; Petryshen et al., 2000; de Kovel et al., 2008). Recently support for an additional dyslexia locus near DYX2 that contributes to a rapid naming phenotype was obtained in a German population (König et al., 2011).

DYX3 on chromosome 2p15–p16 (OMIM 604254) was first identified in a genome-wide scan in a single large Norwegian family (Fagerheim et al., 1999). Evidence supporting this locus has been reported from studies in the United Kingdom (Fisher et al.,

2002a), Canada (Petryshen et al., 2002), Finland (Kaminen et al., 2003), and the Netherlands (de Kovel et al., 2008) but the genetic regions did not consistently overlap.

The DYX4 locus on chromosome 6q13–q16 has only been reported by one group (Petryshen et al., 2001). In this study of 96 Canadian families, the **parametric** and **non-parametric** LOD scores did not reach significance levels usually set as thresholds and this locus is not listed in the OMIM database.

The DYX5 locus (OMIM 606896) was identified in a genome-wide scan in a large Finnish family with impairments in rapid naming, phonological awareness, and verbal short-term memory. Linkage of a categorical dyslexia assessment was detected to the pericentromeric region of chromosome 3p12–q13 (Nopola-Hemmi et al., 2001). In this family, the most severely affected members had poor reading comprehension, a trait that characterizes LI rather than dyslexia (Nopola-Hemmi et al., 2002). This locus has also been implicated in SSD (Stein et al., 2004).

The DYX6 locus on chromosome 18p11.2 (OMIM 606616) was identified by genome scans for multiple quantitative endophenotypes of dyslexia in independent sib pair cohorts from the United States and the United Kingdom (Fisher et al., 2002a). This study detected many secondary signals that provide support for some of the other loci identified in other studies. At least one other large study was unable to corroborate the chromosome 18 locus (Schumacher et al., 2006b). Interestingly, a study of reading ability in a population not selected with respect to this behavior also detected evidence of linkage to this region (Seshadri et al., 2007).

The DYX7 locus on chromosome 11p15 was found by a targeted study of the dopamine receptor D4 (DRD4) as a candidate for dyslexia based on its postulated involvement in Attention deficit/hyperactivity disorder (ADHD) and the frequent co-occurrence of the two disorders (Hsiung et al., 2004). This study utilized a slightly larger set of Canadian families that had been used in the linkage study that yielded DYX4. Neither a significant association with DRD4, nor an excess of the DRD4 seven-repeat **allele** associated with ADHD was found in dyslexic subjects, and no other group has reported supportive evidence for this locus, which has not been assigned a locus designation in OMIM.

Using Rh blood type alleles as markers, one research team found suggestive evidence for linkage of dyslexia defined categorically to *chromosome 1p34–p36* (Rabin et al., 1993). A study of Dutch sib pairs, also using a **categorical affectation status**, obtained supportive evidence for this locus, *now designated DYX8* (OMIM 608995; de Kovel et al., 2008).

The final "named" locus, *DYX9, on Xq27* was identified through a genome wide scan for a categorical diagnosis of dyslexia in a single Dutch family (de Kovel et al., 2004). A signal was also seen near to this location in the genome scan that identified the 18q locus (Fisher et al., 2002a).

Other loci that do not have a DYX appellation have been identified by a variety of approaches, but many have not been corroborated in other subject samples. Utilizing a large set of well-characterized families with dyslexia and modeling the endophenotypes as quantitative traits, we have identified loci that may contribute to pseudoword reading ability on chromosome 2q22.3 (Raskind et al., 2005), real word reading ability on chromosome 13q12 (Igo et al., 2006), phonological memory on chromosomes

4p12 and 12p12–p13 (Brkanac et al., 2008) and spelling performance on chromosomes 2q11–q22, 9q33–q34155, and 15q12–q14 (Rubenstein et al., 2011). By **quantitative transmission disequilibrium testing (QTDT)** and **linear association modeling**, we found evidence that two functionally related genes, *FOXP2* and *CNTNAP2*, that play a role in speech and language impairments, are associated with phonological memory, real word reading rate, and measures of sequential motor ability in our ascertained for dyslexia (Peter et al., 2011b).

In a **genome-wide association study (GWAS)** for mismatch negativity, an electrophysiologic measure related to speech processing, a marker on chromosome 4q32.1 provided significant results in discovery and replication samples. This region does not contain any protein coding genes, but the markers were associated with mRNA expression levels of *SLC2A3* on chromosome 12 that codes for the predominant neuronal glucose transporter (Roeske et al., 2011). The authors speculate that glucose deficits in neurons might cause the attenuated mismatch negativity during passive listening tasks.

For a complex and heterogeneous disorder, it is not surprising that different research groups have identified unique locations and have not always found supportive evidence for locations reported by others. The studies are usually not directly comparable as there are differences in phenotypes evaluated, ascertainment schemes, eligibility criteria, and analysis methods.

OTHER DEVELOPMENTAL DISORDERS WITH FEATURES THAT OVERLAP WITH DYSLEXIA

ATTENTION DEFICIT/HYPERACTIVITY DISORDER

Attention deficit/hyperactivity disorder comprises three behaviorally defined subtypes, predominantly inattentive type (ADHD-PI), predominantly hyperactive-impulsive type (ADHD-PHI), and combined type (ADHD-C; Wolraich et al., 2011; Willcutt et al., 2012), although these may not be fixed and stable distinctions for an individual over time (Frick and Nigg, 2012). ADHD is more frequently observed in males than females (Kronenberger and Dunn, 2003). Many individuals with ADHD also exhibit reading impairment, but slowed processing speed characterizes both ADHD and dyslexia, whereas working memory deficits are associated with dyslexia but not ADHD (McGrath et al., 2011). Given the frequent comorbidity, one hypothesis is that there are shared etiologies. Studies on twins support a predominantly genetic basis for the comorbidity, especially for the inattentive subtype of ADHD (Stevenson et al., 1993; Willcutt et al., 2000, 2007; Nigg et al., 2010). Genome-wide linkage scans have identified multiple loci that may harbor genes for ADHD (Fisher et al., 2002b; Bakker et al., 2003; Ogdie et al., 2003; Arcos-Burgos et al., 2004; Asherson et al., 2008; Faraone et al., 2008; Zhou et al., 2008; Frazier-Wood et al., 2012). Review of the research to date shows that, for the most part, these regions are distinct from those implicated in dyslexia, but there are some overlaps, notably 1p36, 2q22–35, 3p12–q13, 4q12–13, 6p21–22, 6q12–14, 13q22–33, and 15q15–21 (Germano et al., 2010).

Because the regions are very large and contain many genes, it is not clear if these findings reflect **pleiotropy** – the same gene contributes to both disorders – or coincidence – distinct genes for the different disorders reside in the same location. One study directly addressed the issue of pleiotropy by performing a bivariate linkage scan for phenotypes of both disorders in a sample of sibs selected for reading disability (Gayán et al., 2005). A locus on chromosome 14q32 provided evidence for this effect. Another study addressed this issue in reverse – reading ability was studied in a sib sample ascertained for ADHD (Loo et al., 2004). Four regions of suggestive linkage were identified, two of which overlapped with dyslexia signals on chromosomes 16p and 17q that had provided suggestive signals in their previous linkage analysis for ADHD (Fisher et al., 2002b).

The dopamine receptors, particularly DRD4 on chromosome 11p15.5, have been extensively studied as candidates for ADHD. Dopamine receptors have also been studied in dyslexia, but although association of DRD1 with inattentive symptoms in a cohort with dyslexia was observed (Luca et al., 2007), no associations, or sequence alterations were observed for dyslexia and multiple dopamine receptor genes or the dopamine transporter gene even in cohorts that provided evidence for linkage to regions containing dopamine receptor genes (Nopola-Hemmi et al., 2001; Marino et al., 2003; Hsiung et al., 2004; Luca et al., 2007). Therefore, it is unlikely that the DRD genes play a major role in dyslexia.

SPEECH SOUND DISORDER

Speech sound disorder is a childhood disorder that affects the ability to acquire speech that is easily understood. Children with SSD may distort, substitute, omit, or insert speech sounds, arriving at speech output that differs in various ways from the adult target forms (Pennington and Bishop, 2009). Examples of distortion and substitution errors are realizing the /s/ sound with a fronted tongue posture known as a frontal lisp or the /k/ sound as a [t] sound ("tat" for "cat"). Omissions and insertions represent phonologically based speech errors. Examples of omissions are reduced consonant clusters ("top" for "stop") or omitted final consonants ("hou" for "house"), even though the omitted consonants are produced correctly in other contexts such as single consonants or word-initial position. A common example of insertion is an inserted schwa sound ([ə]) into a consonant cluster to create consonant-vowel-consonant-vowel pattern (e.g., "balue" for "blue"), which is less complex in terms of speech production. Epidemiologic and twin studies provided evidence for a genetic contribution to SSD (Lewis and Thompson, 1992; Felsenfeld and Plomin, 1997; Bishop, 2002). Although linkage analyses have been performed in SSD, these have largely been restricted to evaluations of candidate loci implicated in other developmental disorders such as dyslexia, autism, and Prader–Willi syndrome, based on the rationale that disordered speech is frequently comorbid in these disorders (Stein et al., 2004, 2006; Smith et al., 2005; Miscimarra et al., 2007). These studies yielded suggestive evidence for shared gene locations on 1p36–p34, 3p14.2–q13.32 and 6p22, and 15q14–q21. One notable exception to the candidate region approach was a genome wide linkage analysis in a family with a particularly severe form of verbal and oral motor apraxia (i.e., affecting both speech and non-speech oral movements) in the presence of impaired language comprehension and formulation, cognitive deficits, and differences in brain structures (Fisher et al., 1998); this analysis identified a mutation in *FOXP2* as the cause for the autosomal

dominant disorder (Lai et al., 2001). *FOXP2* mutations account for only a small proportion of non-syndromic forms of apraxic speech, referred to as childhood apraxia of speech (CAS; MacDermot et al., 2005; Laffin et al., 2012) and have not been found in other forms of SSD or in LI (Meaburn et al., 2002; Newbury et al., 2002; O'Brien et al., 2003), a disorder that is often comorbid with SSD. Intriguingly, there are suggestive linkage signals for dyslexia on chromosome 7q32, but no mutations in *FOXP2* were found in dyslexic individuals from the six families that contributed to the linkage signal (Kaminen et al., 2003). It is important to note that *FOXP2*-related reading impairment would not meet the criteria for dyslexia because the syndrome includes cognitive impairment. In a carefully phenotyped dyslexia subject set without evidence for LI or SSD we observed associations of *FOXP2* and non-word repetition, a measure of phonological memory, and rapid alternating place of articulation (the /pataka/ task), raising the possibility of this gene's influence on component phenotypes shared by multiple developmental disorders of language (Peter et al., 2011b).

Two recent studies screened genome-wide markers in individuals with CAS. In a sample of 24 unrelated individuals with a CAS diagnosis, 12 showed evidence of deleted or duplicated genetic material on 10 different chromosomes (Laffin et al., 2012). The authors interpret their findings as supportive of a heterogeneous CAS etiology. Our research team explored the genetic basis of SSD using a motor sequencing deficit as a marker of affectation status in a multigenerational family where two of the children had a CAS diagnosis. Although the family was too small to provide statistical evidence for linkage, four regions of interest were revealed in a genome wide microsatellite study, two of which overlapped with previously reported regions for dyslexia, 6p21 for a composite measure of rapid naming (König et al., 2011) and 7q32 for categorical dyslexia diagnosis (Kaminen et al., 2003) and non-word and irregular word spelling (Bates et al., 2007), and a third locus at 7q36 borders on the region containing *CNTNAP2*, a gene that interacts with FOXP2 and is thought to affect the component traits of LI (Vernes et al., 2008). More recently, we showed that the CAS phenotype in multigenerational families was characterized not only by deficits in sequential processing at the level of alternating oral motor movements, which is consistent with the traditional CAS definition as a motor programming disorder, but also by deficits in sequential hand movements, indicating a systemic motor deficit, and by sequential professing deficits at the level of phoneme sequences during word and non-word imitation as well as during non-word decoding and spelling (Peter et al., 2012). This finding may have relevance for dyslexia, as decoding unfamiliar words and spelling words from long-term memory require high loads of sequential processing.

A review of the SSD/reading impairment comorbidity literature reveals that certain subgroups of children with SSD are more likely to also struggle with learning to read, namely children who also have difficulty with comprehending and/or formulating oral language (Sices et al., 2007), children with deficits in phonological processing (Bird et al., 1995), children whose SSD persists into the school years (Nathan et al., 2004), and children with CAS (Lewis et al., 2004).

LANGUAGE IMPAIRMENT

Language impairment, also referred to as specific language impairment (SLI), is a disorder that manifests as deficits in comprehension and/or expression of language in the presence of typical development in other areas. Syntactic awareness and vocabulary can also be deficient and many children with LI begin to talk later than their typically developing peers and produce a smaller number of different words during conversation (Watkins et al., 1995). Low scores in three types of tasks have been proposed as clinical markers of LI. Several studies showed that children with LI struggle with non-word imitation tasks, which tap into phonological processing and short-term memory, significantly more than typical peers (Dollaghan and Campbell, 1998; Weismer et al., 2000). Sentence imitation tasks tap into short-term memory, semantic processing, and syntactic competence, and children with LI imitate sentences with significantly lower accuracy, compared to typical peers (Stokes et al., 2006; Conti-Ramsden et al., 2007). English has finiteness markers such as the third person singular present tense verb suffix /s, z, əz/ ("she gives"). Children with LI have a higher tolerance for missing finite markers when making grammaticality judgments and produce more finite marker errors than typical peers (Rice et al., 1995; Rice and Wexler, 1996). Consequently, LI differs from dyslexia in that dyslexia is defined with respect to written language and especially at the single word level, whereas LI refers to difficulties with spoken language and especially with respect to the interactions of multiple words in terms of syntactic frames and semantic relationships. Downstream effects of dyslexia may include an impoverished vocabulary due to diminished exposure to text as a source of world knowledge, whereas LI may influence reading comprehension due to deficits in deriving syntactic and semantic information from written words. As in the cases of dyslexia, SSD, and ADHD, there is substantial evidence that LI has a genetic etiology (Bishop et al., 1995; Tallal et al., 2001; Hayiou-Thomas, 2008) and several susceptibility loci have been identified, on chromosomes 6, 7, 12, 13, and 17 (Villanueva et al., 2011), 12 (Addis et al., 2010), 13q (Bartlett et al., 2002), 16q (SLI1), and 19q (SLI2), respectively (Bartlett et al., 2002; Consortium, 2002). The locus on chromosome 16 contains two LI candidate genes, *ATP2C2* and *CMIP* (Newbury et al., 2009), and *CNTNAP2* on chromosome 7 has also been shown to influence LI (Vernes et al., 2008). LI and SSD co-occur more frequently than expected under random conditions (Shriberg et al., 1999; Pennington and Bishop, 2009) and children with SSD and concomitant LI are at a higher risk for developing reading disorders compared with children with isolated SSD (Sices et al., 2007). In a sample of children with LI, evidence for linkage to candidate loci for measures of speech and reading ability was found (Rice et al., 2009). This finding may indicate that speech, language, and reading disorders have some shared genetic etiologies that involve multiple genes.

CO-OCCURRENCE OF ADHD, SSD, LI, AND DYSLEXIA

Definitional imprecision complicates estimation of the frequency with which ADHD, SSD, LI, and dyslexia co-occur (Gilger et al., 1992; Cohen et al., 2000; Peterson et al., 2007; Pennington and Bishop, 2009). Impairments in phonological short-term memory, as assessed by one or more non-word repetition tasks,

characterize dyslexia, LI and SSD, and there is evidence for linkage of this phenotypic trait to loci associated with each of these. This observation illustrates the likelihood that there are probably multiple pathways to even the phenotypic components of these disorders. In LI, evidence for linkage of non-word imitation to both SLI1 and SLI2 has been repeatedly obtained (Consortium, 2002; Velayos-Baeza et al., 2007; Falcaro et al., 2008; Newbury et al., 2009), whereas for SSD linkage was observed to DYX2 on chromosome 6p21 (Smith et al., 2005). More detailed information about comorbidity estimates in communication disorders and associated traits can be found in recent reviews (Peterson et al., 2009; Snowling and Hulme, 2012).

CANDIDATE GENES

A review of dyslexia candidate regions and knowledge of suspected genetic etiologies in disorders frequently also characterized by difficulty with learning to read and spell can provide a meaningful platform from which to describe actual candidate genes for dyslexia. At least fourteen candidate genes have been proposed for dyslexia, but to date some have little supportive evidence. Within the three most-replicated dyslexia loci, four candidate genes for dyslexia have been identified: *DYX1C1* in DYX1 on chromosome 15q21 (Taipale et al., 2003b), *DCDC2* (Meng et al., 2005b) and *KIAA0319* (Cope et al., 2005a) in DYX2 on chromosome 6p21, and *ROBO1* in DYX5 on chromosome 3p12–q12 (Hannula-Jouppi et al., 2005).

The DYX1 locus. DYX1C1 (dyslexia susceptibility 1 candidate 1; MIM 608706) was identified in a study of a family with a **structural chromosomal rearrangement**, t(2;15) (q11;q21), that **segregated** with mild intellectual impairment and/or dyslexia (Nopola-Hemmi et al., 2000). The breakpoint on chromosome 15 was 15 Mb distal to the DYX1 linkage region but was found to disrupt a gene of unknown function (Taipale et al., 2003a). The gene was colloquially called EKN1 but later renamed dyslexia susceptibility 1 candidate 1. DYX1C1 is a widely expressed 420-amino acid cytoplasmic and nuclear protein that contains three tetratricopeptide repeat (TPR) domains thought to be involved in protein–protein interactions, and the breakpoint of the translocation was within a TPR domain-coding region (Taipale et al., 2003a).

In an association study of Finnish individuals with and without dyslexia, the minor alleles of two **single nucleotide polymorphisms (SNPs)** in *DYX1C1* were suggested to be of functional significance: −3G > A (rs3743205), because it creates an ELK-1 **transcription** binding site very near the **translation** initiation site, and 1249G > T, because it truncates the protein by four amino acids (Taipale et al., 2003a). The design of this original association study was flawed in that the cases and controls were related. Multiple groups have investigated the relationship of alleles of both polymorphisms to dyslexia phenotypes. Association of one of these putative functional alleles with dyslexia was found in a study of Chinese children (Lim et al., 2011) and with short-term memory in Italian dyslexics (Marino et al., 2007), but other groups found only modest association with the **major alleles** (Scerri et al., 2004; Wigg et al., 2004; Brkanac et al., 2007), and yet others failed to detect an association with any of the alleles (Bellini et al., 2005; Cope et al., 2005b; Marino et al., 2005; Meng et al.,

2005a; Bates et al., 2010), suggesting that none of these SNPs is the susceptibility determinant. However, expression of a construct containing the −3A allele of rs3743205 was lower than one containing the −3G allele when **transfected** into a neuroblastoma cell line (Tapia-Páez et al., 2008). Two other SNPs in the 5′ **untranslated region (UTR)** of DYX1C1 have been reported to associate with dyslexia both singly and in a **haplotype** with rs3743205 (Dahdouh et al., 2009) and to be recognition sites for **transcription factors** TFII-I and Sp1: TFII-1 toboth alleles of rs3743205 and Sp1 to rs16787 (−10310C > A) and rs12899331 (−10567T > C). The transcription factors TFII-I, poly (ADP-ribose) polymerase 1 (PARP1), and splicing factor proline/glutamine-rich (SFPQ) bind to the −3A-containing rs3743205 site to form a complex with DYX1C1 (Tapia-Páez et al., 2008). Therefore, allelic differences in the 5′ UTR of *DYX1C1* may affect its regulation.

The often-reported difference between the prevalence of dyslexia in males and females raises the possibility that hormones may play a role in its pathogenesis. There is some evidence that estrogen replacement does improve reading ability in postmenopausal women (Shaywitz et al., 2003). It has been shown that the rat **homologue** Dxy1c1 interacts with estrogen receptors alpha and beta in primary rat neuronal cells (Massinen et al., 2009). Recent studies in a human neuroblastoma cell line found that estrogen receptor beta and the transcription factor TFII-I are present simultaneously on a region near the *DYX1C1* transcriptional start site. DYX1C1 expression is enhanced by 17β-estradiol (E2) and alleles of SNP rs3743205 affect the regulation of DYX1C1 by estrogen receptor beta (Tammimies et al., 2012a). These observations could imply involvement of estrogen signaling and neuronal migration in dyslexia. Another interesting observation was that when the −3G allele of rs3743205 (that lies within a **CpG island**) was **methylated**, it had a drastic effect on DYX1C1 transcription (Tammimies et al., 2012a). Therefore, it was postulated that this polymorphism might have a functional effect through an estrogen-signaling pathway and/or through methylation-dependent gene activity status, an epigenetic mechanism.

The DYX2 locus proved more complex, as it contains two candidate dyslexia susceptibility genes, *KIAA0319* in the proximal portion and *DCDC2* (doublecortin domain-containing protein 2; MIM 605755) approximately 200 kb distal. These genes were identified by different groups using similar association-based strategies to narrow the linkage region and detect potentially causative variants (Francks et al., 2004; Meng et al., 2005b). Supportive evidence for involvement of *KIAA0319* had been obtained using some of the same subjects (Kaplan et al., 2002; Deffenbacher et al., 2004) and in an independent sample (Cope et al., 2005a; Harold et al., 2006). Variants in the 5′ *UTR* of the gene, where the **promoter** resides, provide the strongest evidence for association, but results are not always significant and not always in the same direction (Couto et al., 2010; Elbert et al., 2011). The minor allele of SNP rs9461045 in the 5′ UTR was shown to reduce expression in neuronal cells (Dennis et al., 2009). This SNP creates a nuclear protein-binding site for a transcriptional silencer, OCT-1, and **RNAi knockdown** of *OCT-1* in a neuronal cell line restores *KIAA0319* expression from the risk haplotype. RNA interference (RNAi) studies subvert a naturally occurring process of post-transcriptional gene

silencing (Carthew and Sontheimer, 2009; Ketting, 2011). In this procedure, plasmids containing short double stranded RNA molecules complementary to part of the coding sequence of a gene are synthesized. These small molecules form a hairpin structure (shRNA) that specifically binds to the normal message and prevents its translation into protein.

Splice variants, protein structure, post-transcriptional modification, and interaction partners of KIAA0319 have been extensively studied. A major transcript is widely expressed in brain, particularly in cerebellum, cerebral cortex, putamen, amygdala, and hippocampus (Velayos-Baeza et al., 2007, 2008, 2010; Levecque et al., 2009). KIAA0319 has a transmembrane domain, but undergoes intramembrane cleavage, after which the soluble cytoplasmic domain translocates to the nucleus and accumulates in nucleoli, suggesting that it may function in a signaling pathway and have a role in the regulation of gene expression (Velayos-Baeza et al., 2010).

Because no causative coding variant has yet been found in *KIAA0319* (or in the other candidate genes), it is reasonable to postulate that changes in regulation of the gene(s) may be the pathogenic mechanisms. Cell- and developmental stage-specific regulation of gene transcription is a complex process involving epigenetic modification of DNA. One such epigenetic tag is acetylation of **histones** that causes relaxation of condensed **chromatin**, comprised of protein and DNA, so that it is accessible to the transcription machinery (Vaissière et al., 2008; Wang et al., 2009). In a retinoblastoma cell line that shares characteristics with neuronal stem cells, the DYX2 region was mapped by a multistep procedure (ChIP-chip) to detect acetylated histones (Couto et al., 2010). In the first part of the procedure (ChIP), chromatin is treated to bind the protein of interest to the DNA (cross-linking) to prevent detachment. The cells are then lysed, the specific protein-DNA complexes are immunoprecipitated with antibody to the protein, and proteins are removed. In the next part of the procedure (chip), the DNA sequence is determined by hybridization to genomic arrays called chips. This approach identified a cluster of acetylated histones that mapped to 2.7 kb within the 5′ region of *KIAA0319*. Multiple SNPs previously associated with differential expression of the gene were contained in this small segment and six additional ones were identified in a 22 kb haplotype block that encompassed this region (Couto et al., 2010). One or more of these polymorphisms might alter transcriptional regulation of *KIAA0319* and thus play a role in dyslexia. For example, as assessed by tandem mass spectrometry of KIAA0319 transcripts in neuroblastoma and lymphoblastoid cell lines, expression was consistently lower from the allele bearing the putative risk haplotype suggesting that it is frequently inherited together with a regulatory sequence variant that negatively affects transcription (Paracchini et al., 2006).

Association of dyslexia with SNPs in the 5′ *UTR* of the *DCDC2* gene has also been found (Deffenbacher et al., 2004; Meng et al., 2005b). Two polymorphisms in *DCDC2* are potential functional variants, a 2445 bp deletion in **intron** 2 and a compound short tandem repeat within the deleted region (BV677278; Meng et al., 2005b). Approximately 17% of dyslexic subjects in a US sample carried the deleted allele and, what seemed even more tantalizing, all subjects with the deleted allele had dyslexia. In addition alleles of BV677278 were recently shown to affect transcription through

an enhancer mechanism (Meng et al., 2011). In an Italian sample set the deletion appeared to associate with severity of impairment on quantitative traits (Marino et al., 2012). However evidence for a causative role of one or both of these polymorphisms has been elusive in other subject samples. We did not observe association of *DCDC2* alleles with dyslexia in our multigenerational US sample, although there was a slight tendency for the intronic deletion to be associated with worse performance on some quantitative measures of dyslexia in the probands, but not in their parents (Brkanac et al., 2007). The German sample that had provided supportive evidence for the DYX2 region (Schumacher et al., 2006a) did not show transmission deviation for either the deletion or the complex STR polymorphism (Ludwig et al., 2008). As is increasingly apparent from burgeoning exome sequencing projects on numerous disorders, the exome of an individual contains 10,000–15,000 variants, including premature stop codons, and these are often phenotypically silent (Ng et al., 2008).

The DYX5 locus. The *ROBO1* gene that encodes an axon guidance receptor was found by identifying the breakpoints of a translocation, t(3;8; p12;q11), in a man with dyslexia and infertility (Hannula-Jouppi et al., 2005). The breakpoint on chromosome 3, in the DYX5 and SSD locus (Nopola-Hemmi et al., 2001; Stein et al., 2004), fell in the first intron of the gene. Interpretation of the family history is complicated by the presence of dyslexia in one sibling and intellectual impairment in his two other siblings, none of which carries the translocation. Because the Drosophila melanogaster homolog of *ROBO1* is involved in formation of neural connections between the left and right brain (Kidd et al., 1998) and because ROBO1 activity was reduced in 19 dyslexic members of the large Finnish family that had provided linkage to this region (Nopola-Hemmi et al., 2001), the authors hypothesized that dyslexia in rare families may be caused by partial **haploinsufficiency** of the gene. SNPs rs6803202 and rs4535189 in *ROBO1*, that have not been shown to have a functional effect, associate significantly with phonological memory but not reading or spelling in an unselected population of twins and their siblings (Bates et al., 2011 #3602). These results led the authors to propose that this gene is a candidate for LI but not dyslexia. Knockout of the mouse homolog, *Robo1*, prevents axons from crossing the corpus callosum and is lethal at birth (Andrews et al., 2006). It was hypothesized that poor axonal crossing might have an effect on binaural hearing in individuals in the Finnish family who carried the risk *ROBO1* haplotype (Lamminmäki et al., 2012). Frequency-tagged magnetoencephalographic (MEG) tests of binaural suppression (Kaneko et al., 2003), an indirect assessment of axonal crossing in auditory pathways, did reveal defective interaural interaction.

Other Proposed Candidate Genes. Several other genes deserve mention, but await corroboration before they can be added to the list of candidate genes for dyslexia susceptibility. *DOCK4* in the AUTS1 locus on chromosome 7q31.1 was proposed as a dyslexia candidate gene in a study of autism. In one Dutch family, autistic siblings carried a maternally inherited microdeletion that created a fusion of *DOCK4* and another gene, *IMMP2L*, and a paternally-inherited microdeletion that disrupted a gene in the contact in associated protein family (*CNTNAP5*) that has been implicated in autism (Pagnamenta et al., 2010). Another sibling did not have a diagnosis of autism but had a reading impairment as did the

mother, one of her brothers, and two of his children. One of the autistic siblings and two other siblings of the mother also carried the microdeletion but were not reading impaired. Given the co-occurrence of the *DOCK4* disruption and reading impairment in six of nine people in the family, a panel of 606 unrelated individuals with dyslexia was evaluated. This study detected a *DOCK4* microdeletion in a boy who inherited it from his father who had slow reading speed; his sister who had no reading difficulties did not carry the microdeletion.

By **fluorescence in situ hybridization (FISH)** and SNP microarray analyses, a small deletion on chromosome region 21q22.3 was found in all four reading disabled members of a family (Poelmans et al., 2009). The deletion involved four brain-expressed genes, *PCNT*, *DIP2A*, *S100B*, and *PRMT2*. It is not known which, if any, of these genes is responsible for the phenotype, but arguments have been put forward in favor of *DIP2A*, because it encodes a protein that interacts with the glutamate receptor (Yu et al., 2001) and might be involved in synaptic plasticity, and *PCNT*, because it encodes a protein required for the assembly of the primary cilium (Jurczyk et al., 2004). Mutations in PCNT cause Seckel syndrome, an autosomal recessive disorder of marked microcephaly and dwarfism (Griffith et al., 2008).

Another potential candidate gene in the DYX1 locus has been proposed. The complex promoter region of *CYP19A1* was disrupted by the breakpoint of a translocation, t(2;15; p12;q21), carried by four people in a Finnish family, one of whom was dyslexic (Nopola-Hemmi et al., 2000; Anthoni et al., 2012). *CYP19A1* codes for aromatase, an enzyme that converts androgens into estrogens (Boon et al., 2010). This is a tantalizing finding in light of the previously mentioned hypothesis that sex hormones may play a role in development of dyslexia. Some evidence for association of SNP haplotypes in CYP19A1 with dyslexia defined categorically was found in Finnish and US dyslexia cohorts, but not in a German one (Anthoni et al., 2012). These same haplotypes also showed association with SSD, a disorder with evidence of linkage to the chromosome 15q21 region. In the dyslexia cohorts, less significant associations were observed for quantitative traits, including oral motor skill and nonsense word repetition, traits that characterize SSD. Two dyslexia-associated SNPs that flank the brain-specific promoter of *CYP19A1* affected the binding of several transcription factors that also bind to *DYX1C1* (Tapia-Páez et al., 2008). Patterns of brain expression of *CYP19A1* paralleled those of *DYX1C1*, *DCDC2*, *KIAA0319*, *ROBO1*, and *C2ORF3* and were most strongly correlated with *ROBO1* and *DYX1C1* (Anthoni et al., 2012). Finally, aromatase knockout mice had evidence of cortical disorganization, including increased neuronal density and occasional **heterotopias**.

Linkage studies in Finnish families implicated loci on chromosomes 2 and 7 in dyslexia (Kaminen et al., 2003). Through association studies in Finnish and German subject samples, two candidate genes, *C2Orf3* and *MRPL19*, were proposed for DYX3 on 2p16–p15 (Anthoni et al., 2007). *C2Orf3* and *MRPL19* RNA was decreased in heterozygous carriers of a risk haplotype. However, little is known about the function of the proteins coded by them, and large association studies of English and Australian children found no support for involvement of this locus in dyslexia (Paracchini et al., 2011; Scerri et al., 2011).

Spurred by a supportive linkage signal for non-word reading in Australian twins for one marker in the chromosome 7q22–q34 locus (Bates et al., 2007), fine mapping, and association studies were done in German and Finnish sample sets (Kaminen et al., 2003). No support for linkage to this region was found in the German sample, but results in the Finnish sample set, expanded from the one used originally to identify the peak, considerably narrowed the region of interest. In this narrowed region, overlapping haplotypes within the diacylglycerol kinase gene *DGKI* were detected in both samples, but only the Finnish association remained significant after Bonferroni correction. DGKI can modulate receptor-dependent responses in processes such as synaptic transmission synaptic transmission (Merida et al., 2008), and thus deserves consideration as a susceptibility gene for dyslexia.

MC5R, DYM, and NEDD4L have been proposed as candidate genes for the dyslexia locus on chromosome 18 (Scerri et al., 2010). These and other genes and loci that showed association with dyslexia in single studies continue to be reported but require confirmation. Many of the observed associations are driven by the subsets of most severely affected individuals.

As mentioned above, the distinction between the various disorders of written language is not discrete and phonological memory impairment characterizes them all. The phenotypic overlap might reflect shared genetic contributions. *GRIN2B* is a candidate gene for the chromosome 12p12 locus for phonological memory identified in our American dyslexia sample (Brkanac et al., 2008); the variant rs1012586 was significantly associated with phonological memory in a German dyslexia sample (Ludwig et al., 2010). Several candidate genes for LI, *CMIP*, *ATP2C2*, and *CNTNAP2*, are also associated with phonological memory (Newbury et al., 2009; Peter et al., 2011b) and variants in *CMIP* (e.g., rs6564903) may affect single word reading and spelling (Newbury et al., 2011; Scerri et al., 2011).

Copy number variation (CNV), a form of DNA derangement increasingly implicated in developmental disorders (Morrow, 2010; Coe et al., 2012) deserves mention. We investigated the role of CNVs in dyslexia, sporadic autism, and intellectual impairment. We observed a gradient of frequency of these changes increasing with more severe intellectual impairment (Girirajan et al., 2011). In more than 350 children with dyslexia, there was essentially no difference in large CNV burden compared to controls.

The potential involvement of dyslexia candidate genes with reading skills in the general population has also been explored. In a longitudinal study of a cohort of English children, associations were observed between *DCDC2* and dyslexia, and between *CMIP* and *KIAA0319* and single-word reading and spelling across the ability range; significance was increased by inclusion of individuals with comorbid LI or ADHD (Scerri et al., 2011). In contrast, no support for involvement of *MRPL19/C2ORF3* in reading abilities was obtained and results for *DYX1C1* were weak. The major allele of rs3743205 (−3G allele) showed a trend of association with poor reading performance, and the minor allele of rs685935 showed a trend of association with poor spelling performance. An association study of markers in *DYX1C1*, MRPL19/*C2ORF3*, *KIAA0319*, and *DCDC2* with quantitative performance on reading comprehension and ability to correct spelling mistakes or

supply missing words was performed in a longitudinal cohort of 520 Australian individuals (Paracchini et al., 2011). This study found that the same three-marker haplotype in *KIAA0319* and the minor allele of SNP rs2143340 that was associated with dyslexia and reduced expression (Paracchini et al., 2008) was also associated with poorer reading and spelling performance in an unselected population and the results were strengthened by adjustment for IQ. Finally, a missense mutation (Val91Ile) in *DYX1C1* was suggested to be functionally related to reading, spelling, and short-term memory in a large set of adolescents not selected for dyslexia (Bates et al., 2010) but this finding has not yet been replicated.

RELATIONSHIPS BETWEEN CANDIDATE GENES AND BRAIN STRUCTURE

A PROPOSED CAUSATIVE ROLE OF BRAIN PATHOLOGY IN DYSLEXIA

For more than 40 years, the existence of anatomic brain correlates of dyslexia have been postulated. From the late 1960s to mid 1980s, abnormalities were detected in autopsied brains from individuals with histories of reading impairment (Drake, 1968; Galaburda and Kemper, 1978; Galaburda et al., 1985). The first case described by Galaburda demonstrated delayed speech development, impairments in semantic and mathematical ability, and epilepsy (Galaburda and Kemper, 1978). Abnormalities were found predominantly in the left hemisphere and included an area of polymicrogyria in the left planum temporale and posterior portion of the transverse gyrus of Heschl, disordered cortical layering in the cingulate gyrus and rostral insula, and minute foci of dysplasia in the parietal, occipital, and temporal lobes. Three additional men were then studied (Galaburda et al., 1985). In addition to reading and spelling impairments, one of these subjects had a very low IQ, one was reported to have "notable" language difficulties, and one had delayed speech acquisition. Neuronal **ectopias** and architectonic dysplasias located mainly in perisylvian regions and affecting predominantly the left hemisphere were found in all three cases. The ectopias are thought to result from abnormal migration of neurons during brain development. The early postmortem studies also suggested that the left and right planum temporale regions were equal in size in the brains of individuals with dyslexia, whereas in typical individuals, the right planum temporale is smaller than its left counterpart (Livingstone et al., 1991; Galaburda et al., 1994). More recent research suggests, however, that this lack of asymmetry is seen more frequently when poor reading ability coincides with poor language ability, compared to isolated poor reading ability (Leonard and Eckert, 2008).

During embryonic brain development, neuronal progenitors go through a proliferation phase, differentiate into postmitotic neurons, and then migrate to specific locations. Defects in neuronal migration can be caused by single gene mutations and often have severe developmental consequences, including cognitive impairment and intractable epilepsy (Liu, 2011). However, there is a wide range of manifestations and severity, representative of the genetic heterogeneity. One of these disease subtypes is periventricular nodular heterotopia (PVNH). A study of 10 individuals with MRI-documented PVNH found that all had current difficulty with phonology, reading, and spelling and most had a history of problems with reading, but only four had IQ measurements more than

a standard deviation below the mean (Chang et al., 2005). A subsequent study found that individuals with dyslexia had more severe phonological impairment that those with PVNH, but both groups had impaired rapid naming, related to reading fluency (Chang et al., 2007). In those with PVNH, diffusion tensor imaging, an MRI-based imaging method to characterize fiber tract anatomy, found that severity of rapid naming difficulty correlated directly with degree of focal disruptions in white matter microstructure and organization in the vicinity of gray matter nodules. The authors proposed that the findings in PVNH, by extension, support the functional association of ectopias and dyslexia and suggest a biological mechanism for the behavioral defect. However, some caution should be exercised in extrapolating directly from PVNH to dyslexia with respect to this mechanism. Widespread neuronal ectopias do not predict existence or pattern of reading impairment (Reinstein et al., 2012) and may be associated with non-verbal learning impairment (McCann et al., 2008).

EVIDENCE FOR INVOLVEMENT OF DYSLEXIA CANDIDATE GENES IN BRAIN PATHOLOGY

It is notable that 10 candidate dyslexia genes are members of a proposed molecular network involved in neuronal migration and neurite outgrowth (*ROBO1*, *KIAA0319*, *KIAA0319L*, *S100B*, *DOCK4*, *FMR1*, *DIP2A*, *GTF2I*, *DYX1C1*, and *DCDC2*; Poelmans et al., 2011) and axon guidance (Hannula-Jouppi et al., 2005; Poon et al., 2011). A role in neuronal migration during brain development has been suggested for multiple dyslexia candidate genes. DYX1C1 is expressed in developing rat forebrain as well as in adult brain (Rosen et al., 2007). To investigate the importance of DYX1C1 protein on brain development, RNAi knockdown experiments were performed (Wang et al., 2006; Rosen et al., 2007). When short DNA pieces containing shRNA specific for the rat homolog (*Dyx1c1*) of human DYX1C1 were injected into rat brains *in utero*, the orderly migration of transfected neurons was disrupted, either traveling too short or too far a distance from the ventricular zone (Wang et al., 2006; Rosen et al., 2007; Currier et al., 2011). In some animals, ectopias were seen in the molecular layer that were similar to the abnormalities previously reported in brains of people with a history of reading impairments. Because GABAergic neurons that did not contain the shRNA were also present in the ectopias, it is postulated that they were affected by the cells that did contain the shRNA (Currier et al., 2011). Knockdown of *DYX1C1* was also associated with auditory processing and spatial learning deficits (Threlkeld et al., 2007).

Working memory deficits have been documented in dyslexic individuals (Swanson and Berninger, 1995; Swanson and Siegel, 2001; Brooks et al., 2011; Martinez Perez et al., 2012) and an association between *DYX1C1* variants and memory deficits has been observed (Marino et al., 2007). Rats treated *in utero* with RNAi of *Dyx1c1* exhibited a subtle, but significant and persistent impairment in working memory as assessed by a radial water maze task (Szalkowski et al., 2011). Recently, gene expression and protein interaction profiling in a human neuroblastoma cell line revealed that DYX1C1 can modulate the expression of nervous system development and neuronal migration genes such as RELN and associate with a number of cytoskeletal proteins (Tammimies et al., 2012b).

Fluorescence *in situ* hybridization revealed a pattern of expression in fetal mouse and human brains at various stages of development that suggested KIAA0319 plays a role in neuronal migration during formation of the cerebral cortex (Paracchini et al., 2006). As was seen for *DYX1C1*, *in utero* RNAi knockdown in rat brain of the rat homolog, *Kiaa0319*, altered neuronal morphology, and disrupted the normal outward migration of neurons from the ventricular zone toward the cortical plate (Paracchini et al., 2006; Peschansky et al., 2010); overexpression did not result in periventricular heterotopias. The ectopias contained both transfected and non-transfected neurons, suggesting that the mechanism of migration disruption is both cell autonomous and non-cell autonomous. In addition, neurons transfected with Kiaa0319 shRNA exhibited apical dendrite hypertrophy, showing that Kiaa0319 is involved in growth and differentiation of dendrites as well as neuronal migration (Peschansky et al., 2010). Embryonic RNAi-knockdown of rodent *Kiaa0319* also results in impaired acoustic discrimination as assessed by a modified prepulse inhibition paradigm (Szalkowski et al., 2012). Furthermore, in the subset of animals that exhibited impaired spatial learning abilities on Morris and radial arm water maze testing, hippocampal dysplasia was seen. However, in contrast to *DYX1C1*, no significant impairment in working memory was detected in these animals (Szalkowski et al., 2012).

DCDC2 protein belongs to the doublecortin domain containing family of genes. Other members of that family have been shown to bind to and stabilize assembly of microtubules, and mutations in mice interfere with neurogenesis, dendrite formation, and neuronal migration (Corbo et al., 2002; Kerjan et al., 2009; Pramparo et al., 2010). Therefore, it has been speculated that the effect of abnormal DCDC2 in dyslexia might be mediated through disruption of microtubule-mediated movement of proteins and cell migration. Although the specific type of gene change in *DCDC2* that is responsible for its effect on reading remains unknown, under the assumption that the pathogenic change would decrease the activity of the protein, RNAi studies were performed. As was seen for *DYX1C1*, knockdown of the rat *Dcdc2* message resulted in neuronal migration anomalies (Meng et al., 2005b; Burbridge et al., 2008). Some neurons migrated only a short distance from the ventricular zone resulting in heterotopias, and others migrated past their expected lamina. Co-transfection of *Dcdc2* shRNA and a human *DCDC2* overexpression construct rescued the periventricular heterotopia phenotype, but did not prevent transfected neurons from migrating too far (Burbridge et al., 2008). Overexpression of either rat *Dcdc2* or human *DCDC2* did not cause any malformations.

The primary cilium is a solitary organelle in most cells that is involved in signaling pathways during development and in homeostasis (Satir et al., 2010). It is comprised of microtubules. A role for DCDC2 in the structure and function of primary cilia was suggested by studies in cultured rat hippocampal neurons (Massinen et al., 2011). In the presence of overexpressed DCDC2, the primary cilia grew longer. Overexpression of human DCDC2 or the *Caenorhabditis elegans* homolog in *C. elegans* caused ectopic branching at the cell soma and dendrites of ciliated neurons. The ciliopathies are a phenotypically varied group of disorders in humans, some of which are characterized by abnormal

development of the central nervous system (Ansley et al., 2003; Dixon-Salazar et al., 2004).

Studies in a knockout mouse model showed that complete loss of Dcdc2 protein was not required for normal brain development (Wang et al., 2011); neuronal migration, neocortical lamination, neuronal ciliogenesis, and dendritic differentiation were all essentially normal. But knockdown of other doublecortin proteins by RNAi resulted in more severe neuronal migration and dendritic abnormalities in *Dcdc2* knockout mice than in wild-type mice. These results indicate that in mice Dcdc2 probably has partial functional redundancy with other doublecortin family members. In contrast to the knockout mice whose performance was indistinguishable from wild-type, mice carrying a heterozygous deletion of *Dcdc2* **exon** 2 were impaired in visual long-term memory, as measured by a test of novel object recognition, and had decreased performance efficiency on maze testing although they retained the ability to learn the task (Gabel et al., 2011). Alteration of visuo-spatial perception is one proposed etiology for dyslexia (Smith-Spark et al., 2003; Vidyasagar and Pammer, 2010).

These studies show that substantial suppression of the dyslexia candidate genes in animals produces brain abnormalities, some of which are similar to what was seen in the postmortem anatomic studies of Galaburda and others. However, no variants predicted to have such a severe effect on the function of the genes have yet been found in dyslexic individuals.

RELATIONSHIPS BETWEEN CANDIDATE GENES AND BRAIN FUNCTION

A comprehensive review of the research over the past three decades on the brain basis for dyslexia and the various imaging tools used to study different aspects of brain structures and functions is beyond the scope of this article; such information is presented in multiple recent publications (Richards et al., 2007; Sandu et al., 2008; Siok et al., 2008; McCardle et al., 2011; Linkersdörfer et al., 2012; Raschle et al., 2012; Vandermosten et al., 2012). In addition to structural abnormalities documented by pathology and imaging (Darki et al., 2012), functional abnormalities (Linkersdörfer et al., 2012) have also been identified. Moreover, it is increasingly clear that genes are involved not only in neural migration early in brain development but also in the functioning of the brain throughout development. Genes play a role in regulating efficiency of glucose utilization (energy supplies; Roeske et al., 2011) and mRNA transcription and translation processes in individual neurons in different regions of the brain (Batshaw et al., 2007; Kandel et al., 2012). In addition, the brain continues to change across development (Linkersdörfer et al., 2012).

Increasingly research attention is being directed to these various roles of genes in brain development, brain structures, and brain functions (e.g., Richards et al., 2006; Darki et al., 2012; Pinel et al., 2012; Wilcke et al., 2012). Studies of the correlation of genetic polymorphisms with interindividual variability in brain activation and functional asymmetry in frontal and temporal cortices revealed that SNPs rs6980093 and rs7799109 in *FOXP2* were associated with variations of activation in the left frontal cortex (Pinel et al., 2012). In the three-gene cluster containing *KIAA0319*, rs17243157 was associated with asymmetry in

functional activation of the superior temporal sulcus (STS). These results suggest that *FOXP2* and *KIAA0319* both play an important role in human language development. Their observed cortical effects mirror previous fMRI results in developmental language and reading disorders, and suggest that a continuum may exist between these pathologies and normal interindividual variability (Pinel et al., 2012). By fMRI a significant main effect was observed for the factor "genetic risk" in a temporo-parietal area involved in phonological processing and a significant interaction effect was observed between the factors "disorder" and "genetic risk" in activation of inferior frontal brain areas in dyslexia (Wilcke et al., 2012). This result hints at the role of *FOXP2* genetic variants in dyslexia-specific brain activation and demonstrates use of imaging genetics in dyslexia research. The neuropsychology, brain bases, and genetics research on related disorders of language development – dyslexia, LI, and SSD – and the relationships of the three disorders to each have been previously reviewed (Peterson et al., 2007).

EPIGENETICS

A now substantial body of research has shown that brain structures and functions change over time in response to both genetic and environmental variables. Attention is increasingly being paid to the role of **epigenetic** influences on phenotypes and disorders. Epigenetic changes are erasable – that is they do not change the underlying DNA sequence. Some epigenetic tags are placed by methylation of DNA, acetylation of histones, or phosphorylation of proteins. In contrast to genetic influences that are passed from one generation to the next, epigenetic influences are transmitted from a cell to its progeny. Such epigenetic tags allow genes to be expressed at specific developmental stages and in specific tissues and some are involved in learning and memories. The localization and function of regulatory elements in the genome are being studied through the multisite consortium Encyclopedia of DNA Elements (ENCODE; Dunham et al., 2012).

The role of epigenetics is now being explored to investigate how environmental influences may alter genetic expression at both the brain and behavioral levels. The first step is to characterize the observable/measurable changes. The brain's response to reading, writing, and math instruction has been recently reviewed (Berninger and Dunn, 2012). Interdisciplinary research is advancing knowledge of brain-genetics-and behavioral assessment/instructional research (Richards et al., 2006). This research team drew on neuroanatomical (Eckert and Leonard, 2000; Eckert et al., 2003, 2005 #3674), family genetics (Raskind et al., 2005; Igo et al., 2006; Rubenstein et al., 2011), functional imaging, and related intervention studies (Berninger and Richards, 2010) to provide a converging, cross-disciplinary model for a working memory architecture supporting written language learning. This architecture has a distinct brain signature for storing and processing phonological, orthographic, and morphological word forms and mapping them onto one another. Both biological phenotypes (brain structures and brain functions) were shown to differentiate those with and without dyslexia before but not after specific kinds of language instruction.

CONCLUSION

Progress is being made in understanding the genetic and behavioral variability in learning to read. Clearly, there are compelling links among the findings from studies of genetic linkage and association, functions of candidate genes, brain structures and functions, and associated speech and language abilities. In part, the composite picture of reading disability that has emerged to date is complicated by methodologic issues such as evaluation of different traits in different participant samples. If dyslexia is heterogeneous, studying a sample of individuals from different families means studying a mixture of genetic etiologies. Continued progress will benefit from exploring the complex relationships between the genetic and behavioral variations and requires cross-disciplinary, cross-site collaborations for fruitful progress. Teams should include educators and educational psychologists as well as geneticists, neuroscientists, and clinical linguists.

GLOSSARY OF GENETIC TERMS

Allele: a piece of DNA that has two or more possible states in the population.

Association: if a certain genetic variant is more common in a group of individuals with a certain trait than in a group of individuals without the trait, it is said to be associated with the trait.

Categorical affectation status: term used to label an individual as having a disorder or not.

Centromeric: term referring to a location in or near a chromosome's centromere, a region that serves as a physical connector when two paired chromosomes attach to each other during a part of cell division.

Chromatin: the DNA with the proteins that allow it to be condensed in the nucleus.

Complex disorder: a disorder thought to result from the effects of multiple genes simultaneously. Environmental factors can influence the disorder as well. This is in contrast to Mendelian disorders, which are caused by disruptions in single genes.

Copy number variation (CNV): regions of the genome that are duplicated or deleted. Some CNVs are polymorphic in the population or do not involve genes and have no discernable phenotype, whereas others cause disease.

CpG islands: short DNA sequences that contain a high frequency of neighboring CG dinucleotides. They are usually located at or near the transcription start site of genes. The cytosines in these configurations are subject to methylation. Dense CpG methylation is often associated with silencing of a gene.

Cytogenetic: referring to structures and functions of chromosomes in cells.

Distal: directional term referring to a location on a chromosome that is closer to chromosome's end point given a reference point.

Ectopia: a collection of cells in the wrong location.

Endophenotype: a measurable aspect of a disorder that may not be an obvious symptom of the disorder itself but that has a clear genetic origin.

Epigenetic: refers to heritable changes in gene function where the DNA sequence itself remains unchanged.

Exon: a portion of a gene that is included in the messenger RNA. Genes are comprised of exons and introns.

Familial clustering: the observation of higher prevalence rates of a disorder among biologically related individuals compared with the general population – also referred to as familial aggregation.

Fluorescence in situ hybridization (FISH): fluorescent probes that bind specifically to complementary DNA or RNA. Fluorescence microscopy can be used to detect the location of the fluorescent probe on a chromosome or to identify which cell type or tissue expresses the RNA.

Genome: the entire DNA sequence in an individual.

Genome-wide association study (GWAS): in samples of individuals with, and without, a trait of interest, markers across the entire genome are tested for association with the trait.

Haplotype: a sequence of DNA nucleotides, markers, or genes located in close proximity on a chromosome and inherited together.

Haploinsufficiency: when presence of only one working copy of a gene does not produce enough of the protein product to have normal function.

Heritability: the proportion of variability of a trait in a sample of individuals that is caused by genetic factors.

Heterogeneity: a disorder can look similar across several families, but when different genes cause the disorder in different families, the disorder is heterogeneous.

Heteromorphism: an alternate chromosomal structure.

Heterotopia: periventricular heterotopia is a condition in which neurons do not migrate properly during fetal brain development and form clumps neat the ventricles rather than moving outward to their intended layer of the cerebral cortex.

Histone: proteins that attach to DNA to form chromatin.

HLA locus: a region on chromosome 6 where many genes belonging to the human leukocyte antigen (HLA) system reside. This region is of importance for the human immune system.

Homolog: genes of similar structure and function are called homologs.

Intron: short for "intervening sequence," the portion of a gene that separates the exons. The introns are removed from the RNA before it is translated into protein.

Linear association modeling: testing to determine whether the magnitude of a given trait is correlated with the number of a suspected risk variant. As diploid organisms, humans can have 0, 1, or 2 copies of a risk variant. If individuals with 2 copies show significantly higher levels of the trait than individuals with 1 or 0 copies, there is evidence of genetic association.

Linkage: certain genetic variants that are observed in the presence of certain traits are said to be in linkage with each other. Frequently, linkage is due to the fact that genetic regions that are located within close proximity on the same chromosome are inherited together.

Locus (plural: loci): a specific piece of DNA, described by its location on a given chromosome.

Logarithm of odds (LOD) score: the likelihood of observing a set of test data given that two genomic regions are linked with each other is compared to the likelihood of obtaining these results in the absence of linkage. The logarithm of this ratio is the log odds score, and it is widely used as a statistic to measure evidence of genetic linkage.

Long arm: most chromosomes have a shorter and a longer segment, measured from the endpoint to the centromere. The longer segment or arm is referred to as the q arm, whereas the shorter segment or arm is called the p arm.

Major allele: when two or more variants of a piece of DNA exist in the population, the most commonly found variant is called the major allele.

Methylation: certain DNA sequences can be modified by addition of a methyl group, comprised of one carbon and three hydrogen atoms, to cytosine – one of the four nucleotide types. When certain parts of a gene are highly methylated, it is inactivated and there is no expression and no protein produced.

MIM: acronym for Mendelian Inheritance of Man, a comprehensive catalog of disorders with a genetic etiology. MIM numbers refer to these catalog entries that can be accessed online at OMIM (http://www.ncbi.nlm.nih.gov/omim/).

Models of transmission: how a trait is inherited in given families can be estimated by observing the distribution of the trait among the relatives. For instance, if the trait is present in successive generations and approximately half of the children of a person with that trait also have it, an autosomal dominant model may fit this configuration best. An example of this form of inheritance is Huntington disease. Another model of transmission is autosomal recessive, where the trait is usually found in siblings but not in the parents who both carry a risk allele for the trait. An example of this type of inheritance is cystic fibrosis.

Non-parametric: non-parametric statistical approaches to evaluating genetic markers for evidence of being inherited along with a disorder do not assume any particular modes of inheritance.

Parametric: parametric statistical approaches to evaluating genetic markers for being inherited along with a disorder are based on the parameters of an assumed mode of inheritance, e.g., autosomal dominance.

Phenotype: an observable characteristic that may or may not have a genetic origin. A phenotype can be qualitative, such as normal or impaired reading, or quantitative, such as performance on a behavioral test. Both types of phenotypes have been used in genetic studies of reading impairment.

Pleiotropy: a single gene can affect multiple observable traits.

Promoter: a piece of DNA that is crucial for initiating the process of transcribing a gene's DNA into RNA.

Quantitative transmission disequilibrium testing: testing to determine whether certain genetic variants are transmitted more frequently than expected by chance from an affected parent to an affected child. The term "quantitative" refers to a quantitative characteristic, as opposed to a binary one.

Recurrence risk: the risk that a younger sibling of a child with a certain disorder will also have this disorder.

RNAi, shRNA: the process of RNA interference (RNAi) uses short RNA molecules that can form a hairpin structure (shRNA). The synthesized shRNAs decrease translation from naturally occurring RNA that contains a complementary sequence.

Segregate: a disorder is inherited along with the chromosome on which the causal gene resides. During meiosis to generate sperm and ova, the two copies of a chromosome separate (segregate) into the two haploid gametes that are produced from a single diploid cell.

Single nucleotide polymorphism (SNP): a single base pair that has an alternate form in the population. An individual can carry two copies of one type, two copies of the other type, or one copy of each.

Splice variants: after transcription from genomic DNA to mRNA, during which the intronic sequences are removed, one or more protein-coding exons may be spliced out. The different RNA forms are called alternative transcripts and their protein products (isoform) may have different patterns of tissue localization and different activities.

Structural chromosomal rearrangement: during meiosis, errors can occur such that pieces of a chromosome are deleted, duplicated, or moved to a different chromosome, all of which result in an altered chromosome structure.

Targeted genetic studies: when there are reasons to suspect that a certain gene is causal or that a causal gene resides in a certain part of a chromosome, this gene or genomic region is given preference for genetic analysis over other genes, regions, or even the whole genome.

Transcription: the process of producing messenger RNA (mRNA) from its corresponding DNA.

Transcription factor: a gene product that regulates the function of another gene.

Transfect: insertion of genetic material into cells.

Translation: in molecular biology this refers to the process of producing a protein based on the sequence of the corresponding mRNA.

Untranslated region (UTR): pieces of DNA that are part of a gene but that do not code for a protein.

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Numerical transcoding proficiency in 10-year-old schoolchildren is associated with gray matter inter-individual differences: a voxel-based morphometry study

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Are individual differences in numerical performance sustained by variations in gray matter volume in schoolchildren? To our knowledge, this challenging question for neuroeducation has not yet been investigated in typical development. We used the Voxel-Based Morphometry method to search for possible structural brain differences between two groups of 10-year-old schoolchildren ($N = 22$) whose performance differed only in numerical transcoding between analog and symbolic systems. The results indicated that children with low numerical proficiency have less gray matter volume in the parietal (particularly in the left intraparietal sulcus and the bilateral angular gyri) and occipito-temporal areas. All the identified regions have previously been shown to be functionally involved in transcoding between analog and symbolic numerical systems. Our data contribute to a better understanding of the intertwined relationships between mathematics learning and brain structure in healthy schoolchildren.

Keywords: mathematics learning, number processing, educational neuroscience, schoolchildren, gray matter, voxel-based morphometry, neuroeducation

INTRODUCTION

How are individual differences in numerical cognition associated with structural brain variations in schoolchildren? Not only developmental maturation but also experience and learning may modify brain structure. On one hand, brain maturation is characterized by loss of gray matter (GM) with age that varies according to brain region (Gogtay et al., 2004). On the other hand, experience-dependent structural plasticity was demonstrated by an increase of GM in cerebral areas associated with training function in expert groups (e.g., mathematicians, Aydin et al., 2007) and was demonstrated during intensive trainings (e.g., motor learning, Draganski et al., 2004; or cognitive training, Draganski et al., 2006). The aim of the present study is to provide insights into the relationships between individual differences in mathematics and brain structure (GM volume variations) in 10-year-old typically achieving schoolchildren. As suggested by Carew and Magsamen (2010), linking brain research to education is extremely important for a better understanding of how children learn. It seems central that studies concerning brain plasticity, such as our study, bring information to the educational community in order to contribute to a better quality of education and an adapted pedagogy. However, direct applications within the classroom were still difficult to consider (Hook and Farah, 2012).

Numerical cognition is fundamental for everyday life activities, arises early in development (Feigenson et al., 2004; Cordes and Brannon, 2008) and improves significantly with the emergence of symbolization thanks to language acquisition and academic learning (Gelman and Butterworth, 2005). During schooling, children learn a wide range of mathematics skills. For instance, the first mathematics learning involves associating a quantity (analog system) with its symbol (oral or written numerical word, hereafter called the symbolic system). This transcoding between analog and symbolic systems is essential for developing sophisticated numerical tools (Holloway and Ansari, 2009; Mundy and Gilmore, 2009).

Numerical cognition has been extensively investigated in functional Magnetic Resonance Imaging (MRI) in children (e.g., Ansari et al., 2005; Ansari and Dhital, 2006; Cantlon et al., 2006; Kaufmann et al., 2006). Recent functional MRI meta-analyses collected these studies and indicated that numerical cognition mainly involved a frontoparietal network constituting the right inferior and the left superior frontal gyri and the upper part of the left middle occipital gyrus near the junction with the parietal cortex (Houdé et al., 2010; see also Kaufmann et al., 2011). The recruitment of the frontal network could be one of the first cortical systems that associate non-symbolic numerosities and symbolic

numbers (Nieder and Dehaene, 2009; Opfer and Siegler, 2012). A fundamental region implicated in numerical cognition in adults and children, the intraparietal sulcus (IPS), is increasingly involved during childhood due to academic learning (Rivera et al., 2005; Nieder and Dehaene, 2009; Zamarian et al., 2009). In adults, Aydin et al. (2007) examined the effect of mathematics expertise in two groups and showed less GM in the parietal regions of non-experts. In children, structural MRI studies are scarce and have only investigated individual differences by comparing dyscalculic and control children (Isaacs et al., 2001; Molko et al., 2003; Rotzer et al., 2008; Rykhlevskaia et al., 2009). The results indicate that dyscalculic children present with less GM, especially in parietal and frontal brain areas such as the IPS or the middle and inferior frontal gyri. Inter-individual differences are a rich source of information to link human cognition to cerebral anatomy (Kanai and Rees, 2011). However, we know of no study that has directly examined this relationship in typical development.

The aim of our study is to compare typically achieving school-children of the same age with different levels of expertise in numerical cognition. For this comparison, we used the Voxel-Based Morphometry (VBM) method (i.e., an analysis that allows the detection of volumetric brain variations between two groups of subjects and their localizations after separating gray and white matter from brain anatomical MRI images, see Ashburner and Friston, 2000). We searched for possible neuroanatomical differences between the numerical cognition performances of two groups of 10-year-old schoolchildren, only differing in their numerical transcoding proficiency (i.e., the representation of numerical magnitude, the core of number processing, and its link to numerical symbols). We used two standardized subtests (i.e., number line task and visual estimation of quantities task) from the ZAREKI-R, a mathematical cognition battery (Von Aster and Dellatolas, 2006) that allows assessment of the transcoding proficiency of the children. These two subtests address the representation of numerical magnitude and its link to numerical symbols: the transcoding processing from the symbolic system to the analog system (number line task) and the transcoding processing from the analog system to the symbolic system (visual estimation of quantities task). According to developmental maturation data (Gogtay et al., 2004), one would expect that the higher level group would present a loss of GM in some brain areas due to a more advanced maturation in agreement with a "synaptic pruning" phenomenon (i.e., a fundamental neural plasticity mechanism that may underlie selective behavioral specialization, see Edelman, 1993). Alternatively, from an experience-dependent structural changes perspective, one would expect that better performance would depend on an increase in GM. For the first time, our study seeks to contribute to a better understanding of this important open issue regarding the intertwined relationships between maturation, experience, and learning in typical developing children.

MATERIALS AND METHODS
PARTICIPANTS
Twenty-two children recruited from schools in Caen (Calvados, France, forth grade, $N = 14$, fifth grade, $N = 8$) participated in this study (mean age ± SD, 10 years ± 7 months; age range: 9.2–11.1 years; 11 girls; 19 right handed). They had no history of neurological disease and no cerebral abnormalities as assessed by their T1-weighted MRI. The local ethics committee (CPP Caen Nord Ouest III, France) approved the study. Written consent was obtained from the parents and the children themselves after detailed discussion and explanations.

STANDARDIZED MEASURE OF NUMERICAL TRANSCODING PROFICIENCY
The children passed a whole test battery that was individually administered at school, including the Neuropsychological Test Battery for Number Processing and Calculation in Children (ZAREKI-R, Von Aster and Dellatolas, 2006, French version). We focused on two tasks that allow assessment of numerical transcoding proficiency: number line task and visual estimation of quantities task. The duration of the two paper-pencil tests was approximately 10 min, and the children were first presented with the number line task and then with the estimation of quantities task. These subtests address the representation of numerical magnitude and its link with numerical symbols: transcoding from the analog system to the symbolic system and *vice versa*. In the task requiring estimation of visual quantities, the child had to verbally estimate a number of objects that were quickly presented (dots, glasses, balls). For example, 14 dots were presented on a sheet of paper for 2 s, and the child had to estimate how many dots were present. The child could obtain a maximum score of 5 points (one point was given for each correct response). In the number line task, the child had to place a number (oral or visual presentation) on a vertical line ranging from 0 to 100. For instance, the child had to indicate with a drawing pencil on a sheet of paper where the number "56" was on the vertical line marked from 0 to 100. The child could obtain a maximum score of 24 points (two points were given for each correct response). We then transformed the raw scores for the two tasks into Z-scores (see Earnst and Kring, 1999; Foy and Mann, 2013). To detect group differences based on numerical transcoding proficiency, a composite measure was computed by adding the Z-scores for these two tasks across all children. To verify that our two groups differed only in numerical transcoding proficiency, we also assessed mental calculation (ZAREKI-R, mental calculation task, Von Aster and Dellatolas, 2006, French version), reading ("L'Alouette-R," Lefavrais, 2005) and working memory (WISC-IV, digit span subtest, Wechsler, 2005, French version) abilities.

MRI ACQUISITION
The children were familiarized individually for MRI investigation in a half-hour-long session at school the day before the MRI. This session consisted of a "statue game" in which they needed to stay as still as a statue in a toy tunnel imitating the MRI scanner and its technological environment, including the recorded noises of all MRI sequences, cardboard head coil and medical tape on the forehead (Houdé et al., 2011). The same familiarization process was repeated just prior to the experiment. Anatomical scans were acquired on a 3T MRI scanner (Achieva, Philips Medical System, Netherlands) at the Cyceron biomedical imaging platform (www.cyceron.fr) in Caen (Calvados, France)

using a 3D T1-weighted spoiled gradient (FOV: 256 mm; isotropic voxel size: 1.33 mm; 128 slices; matrix size 192 × 192 voxels; 5 min 7 s duration). Data were acquired while the children passively watched a cartoon on an MRI-compatible screen. The sedative effect of audio/visual systems on children in MRI scanners has been demonstrated; it reduces head motion, provides a positive experience, and decreases wait times (Lemaire et al., 2009).

DATA ANALYSIS

The T1 scans were spatially normalized and segmented into three tissue classes (i.e., gray matter, white matter, and cerebrospinal fluid) with SPM5 (statistical parametric mapping) software (Wellcome Department of Cognitive Neurology, London, UK, www.fil.ion.ucl.ac.uk/spm) implemented in Matlab version 7.4 (Mathworks, Inc., Natick, MA, USA) using a specific template based on the T1-weighted scans (55 MR scans of typically developing children aged 5–12 years acquired with the same MRI scanner and including children's images acquired in the present study). A factorial VBM analysis (Ashburner and Friston, 2000) comparing the two groups of children was performed using SPM5 software on normalized, modulated, and 8 mm FWHM Gaussian-smoothed GM volumes. This analysis included a total brain volume correction for each subject, brain volume values being included as a global calculation in the SPM model. The results reported thereafter were obtained for p values corresponding to $p < 0.001$ uncorrected with clusters with a minimum of 80 voxels. VBM analysis was performed using two-sample t-tests contrasting the two groups including age as covariate.

RESULTS

BEHAVIORAL RESULTS

The children were grouped according to their numerical transcoding proficiency composite Z-score. Children were included in the low numerical transcoding (LNT) group if their composite Z-scores were negative and in the high numerical transcoding (HNT) group if their composite Z-scores were positive, with 10 and 12 children, respectively. According to ZAREKI-R standardization (number line task mean ± SD = 17.63 ± 3.73; and visual estimation of quantities task mean = 3.98 ± 1.01), all the children in the LNT group exhibited at least one score in the second

quartile (number line task = 15–18.25; and visual estimation of quantities task = 3–4), while all the children in the HNT group displayed at least one score in the third quartile (number line task = 18.25–22; and estimation task = 4–5). Importantly, the mean performances of the LNT group on both tasks were in the second quartile, while the mean performances of the HNT group were in the third quartile. The composite scores differed significantly between the two groups [t (20) = −7.58, $p < 0.0001$, $d = -3.39$] but importantly, the groups did not differ according to sex ($p > 0.19$, Fischer's exact test), handedness ($p > 1$, Fischer's exact test), age [t (20) = −0.33, $p > 0.74$, $d = -0.15$], or months of education [$t(20) = 0.30, p > 0.76, d = 0.13$]. Moreover, they did not differ according to mental calculation [$t(20) = 0.27$, $p > 0.79, d = 0.12$], reading [$t(20) = -0.86, p > 0.40, d = -0.39$], and working memory [$t(20) = -0.67, p > 0.50, d = -0.30$] performances (see **Table 1**). Note that there were equal numbers of fifth grade children in the LNT group ($n = 4$) and in the HNT group ($n = 4$).

VBM RESULTS

The contrast analysis demonstrated that the children in the LNT group had less GM volume than the children in the HNT group in a network including parietal, temporal, and occipital cortices (see **Figure 1** and **Table 2**). The identified parietal regions were the right angular gyrus and left inferior parietal gyrus along the intraparietal sulcus extending to the angular gyrus. The temporal regions were the right pole of the middle temporal gyrus extending to the parahippocampal and fusiform gyri, and the left superior, middle and inferior temporal gyri. Finally, the occipital regions included the left middle occipital gyrus and the cuneus extending to the superior occipital gyrus. The children in the LNT group did not have significantly larger GM volumes than the children in the HNT group in any brain region.

DISCUSSION

The relationships between children's numerical transcoding proficiency and cerebral anatomy in the typical developing brain were, to our knowledge, investigated for the first time here. To address

Table 1 | Participant characteristics by group.

	LNT ($N = 10$)			HNT ($N = 12$)			p Value
	Mean	**SD**		**Mean**	**SD**		
Age (months)	120	7.5		121	7.0		ns
Number line score	16.9	3.1		20.3	2.0		0.005
Visual estimation score	3.3	1.2		5.0	0		0.0005
Composite Z-score	−1.4	0.9		1.2	0.6		0.0001
Calculation score	37.8	4.1		37.3	5.3		ns
Reading scores	267.6	93.8		298.4	73.1		ns
Working memory scores	15.9	2.6		16.2	4.6		ns

LNT, low numerical transcoding; HNT, high numerical transcoding.
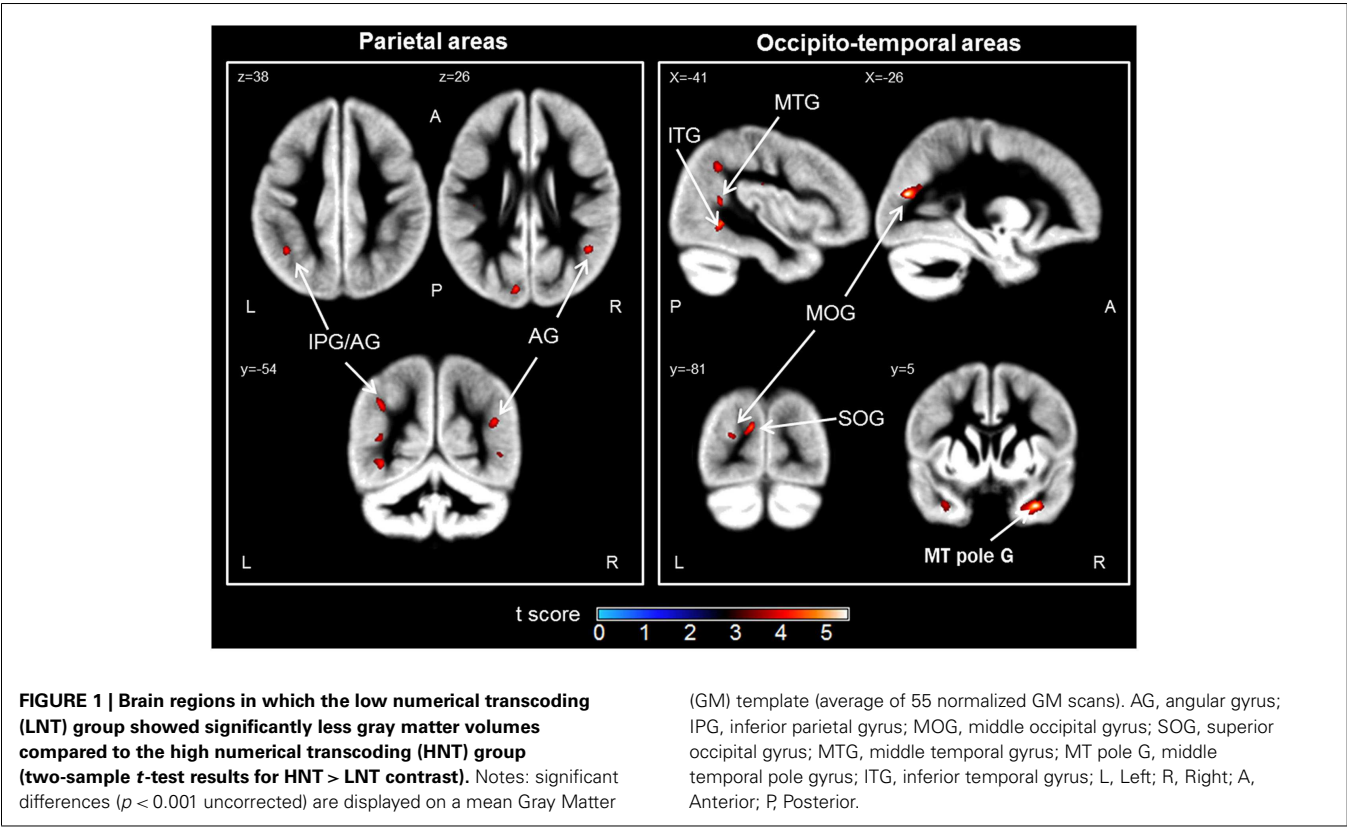
SD, Standard deviation, ns, $p > 0.05$.

FIGURE 1 | Brain regions in which the low numerical transcoding (LNT) group showed significantly less gray matter volumes compared to the high numerical transcoding (HNT) group (two-sample *t*-test results for HNT > LNT contrast). Notes: significant differences ($p < 0.001$ uncorrected) are displayed on a mean Gray Matter (GM) template (average of 55 normalized GM scans). AG, angular gyrus; IPG, inferior parietal gyrus; MOG, middle occipital gyrus; SOG, superior occipital gyrus; MTG, middle temporal gyrus; MT pole G, middle temporal pole gyrus; ITG, inferior temporal gyrus; L, Left; R, Right; A, Anterior; P, Posterior.

Table 2 | Anatomic localization (AAL, Anatomical Automatic Labeling), localization extent and Montreal Neurological Institute (MNI) coordinates of brain areas that showed less gray matter volumes in children.

Anatomical localization (AAL)	Hemisphere	Number of voxels	MNI Coordinates			z-Value
			X	Y	Z	
HNT > LNT						
Angular gyrus	R	122	45	−53	26	3.56
Inferior parietal gyrus (intraparietal sulcus), angular gyri	L	118	−41	−54	38	3.43
Middle temporal pole, parahippocampal, fusiform gyri	R	855	34	5	−35	4.17
Middle and inferior temporal gyrus	L	140	−40	−52	−4	3.73
Superior temporal gyrus	L	89	−66	−10	2	3.64
Middle temporal gyrus	L	86	−41	−52	12	3.51
Middle occipital gyrus	L	342	−26	−77	18	4.17
Cuneus and superior occipital gyrus	L	242	−10	−83	23	3.94
HNT < LNT						
No significant difference						

L, left; R, right.

this open issue, we used the standard VBM approach to detect differences in GM in two groups of 10-year-old, typically achieving schoolchildren varying in level of transcoding proficiency.

Our results demonstrated that children with low numerical transcoding have less GM volume in parietal and occipito-temporal areas than children with high numerical transcoding. Parietal regions are crucial in number cognition (Dehaene et al., 2003; Ansari, 2008; Nieder and Dehaene, 2009). According to the triple code model of number processing (Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 2003), numbers are represented in three distinct systems that serve different functions and that have distinct functional neuroarchitectures related to performance on specific tasks: an analog, a verbal, and a visual system. In this model, parietal areas would be the core of the analog system, corresponding to the representation of the quantity. At the neuroanatomical level, structural differences related to competences

have been identified in parietal areas in atypical development such as dyscalculia (Isaacs et al., 2001; Molko et al., 2003; Rotzer et al., 2008; Rykhlevskaia et al., 2009). Indeed, dyscalculic children, known to present deficits in the "number sense" (i.e., difficulties in understanding a quantity and in number sense access), exhibited GM loss in bilateral parietal areas compared to control subjects. Moreover, one study examined the effect of mathematics expertise between two adult groups (Aydin et al., 2007). The data indicated a GM decrease in parietal regions in non-expert. Our results are in agreement with these studies. A poorer performance seems be related to lower GM volume in parietal areas even in typically achieving children.

It is known that three circuits co-exist in the parietal region (Dehaene et al., 2003): (i) the bilateral horizontal segment of the intraparietal sulcus (IPS) supports quantity processing, (ii) the left angular gyrus (AG) supports manipulation of numbers in verbal form, and (iii) the bilateral posterior superior parietal lobe supports spatial attention processes. We found GM volume changes in the left IPS, a region that has previously been identified in our number processing functional meta-analysis (Houdé et al., 2010). This is a core parietal region implicated in numerical cognition (i.e., number sense) and in magnitude judgment. We also observed GM changes in bilateral AG, which is functionally involved in the transition from quantity-based processing to automatic fact retrieval (Dehaene et al., 1999; Grabner et al., 2007, 2009a; Ischebeck et al., 2007), the processing of digits (Price and Ansari, 2011), or the mapping between a symbol and its referents (Ansari, 2008; Grabner et al., 2009b). Interestingly, the AG has also been involved in non-symbolic number processing (Göbel et al., 2001; Kaufmann et al., 2011). Furthermore, competence-related differences were observed in functional activations of the left AG depending on the level of mathematic competence (Grabner et al., 2007, 2009b). The higher-competence group showed a stronger activation during an arithmetic task. We hypothesize that these functional modulations would be based on structural differences. In our opinion, the GM volume variations observed in the left IPS and the bilateral AG suggest specific expertise-dependent plasticity of these regions. Our tasks assessed transcoding between the analog system and symbolic system, such as Arabic digits or number words. For instance, when the experimenter tells him/her a number, the child must place it on a number line. Children who are less successful in these tasks are less efficient in the transcoding between analog and symbolic systems. Lower performance in the representation of the quantity and in the transcoding of one code to another is associated with less GM volume the IPS and AG brain areas, which are known for their roles in the analog system and in the symbolic manipulation of numbers.

Our study also revealed a GM change according to the level of transcoding proficiency in the left middle and superior temporal gyri, which are involved in the number verbal system previously described in the triple code model of number processing. We also observed GM modulation in such regions of the ventral visual stream as the cuneus, the superior occipital gyrus, the occipital lateral gyrus and the inferior temporal gyrus. While most studies of numerical cognition have focused on the dorsal stream, little attention has been paid to the ventral visual stream, which is thought

to support recognition and discrimination of visual objects, such as digits (Milner and Goodale, 2008; Rosenberg-Lee et al., 2011). The temporal lobe seems to play a role in the link between symbols and the meaning of numbers (Jefferies et al., 2005; Julien et al., 2010). The right anterior temporal cortex, known for its involvement in semantic processing (Visser et al., 2010), also showed GM volume modulation according to the level of transcoding proficiency. Interestingly, Rykhlevskaia et al. (2009) found abnormalities in this area in dyscalculic children compared to control subjects and suggested that it may be an additional fundamental locus in the numerical cognition, perhaps as the semantic memory representation.

Finally, we did not observe GM differences in frontal areas. As suggested by Nieder and Dehaene (2009) and Opfer and Siegler (2012), the recruitment of the frontal network could be one of the first cortical areas that associates non-symbolic numerosities and symbolic numbers. With age, there may be a shift from the frontal cortex to the parietal cortex to perform numerical tasks (Rivera et al., 2005; Houdé et al., 2010). Here, the numerical tasks were relatively easy for 10-year-old children. They learn the association between a quantity and its symbol (number words then digits) from the start of their schooling. The link is already formed, even if it is imperfect in some children. Thus, for this type of task at this age, GM differences observed in the posterior regions could better explain the present results than differences in anterior areas. Indeed, as suggested by Butterworth et al. (2011), a link between the occipito-temporal and the parietal cortex is required for transcoding number symbols onto the numerosity representation.

Taken together, our data may reflect the structural modulation relating to numerical transcoding proficiency in the brain areas dedicated to the transcoding between a quantity and its symbol. One could wonder why the GM volume increases rather than decreases with performance. Cerebral maturation is characterized by a loss of GM with age due to a neural plasticity mechanism called "synaptic pruning" (Gogtay et al., 2004). However, as suggested by Kanai and Rees (2011), GM microstructure could be different, such as GM with more neurons (expertise) or GM with fewer synapses (maturation). Our results with typically developing children highlight this paradoxical period during which the effects of maturation and academic learning are strongly intertwined. Thus, we suggest that intensive learning during schooling could modulate children's brain structure and lead to increased GM volume with performance, as has been observed in adults (Draganski et al., 2004, 2006; Aydin et al., 2007). However, further studies will be necessary to disentangle the intertwined relationships between maturation and learning in the developing brain.

In conclusion, our study, linking numerical transcoding proficiency with brain structure in schoolchildren, contributes to a better understanding of how mathematics learning can modulate brain regions involved in the numerical transcoding. Even if our results were consistent with the numerical cognition literature, it is important to consider them with caution because of the limited number of participants and the use of non-corrected thresholds. It will be interesting to examine the impact of pedagogical interventions on structural brain variations using a neuroeducational approach. For instance, future work will investigate the

potential brain variations induced by the use of numerical games, which appear to have a positive effect on number sense access in populations at risk for mathematical difficulties (Wilson et al., 2009). Neuroeducation could undoubtedly offer an exciting new method for future studies to form a link between education and developmental cognitive neuroscience in regard to mathematics learning.

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Building a functional multiple intelligences theory to advance educational neuroscience

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A key goal of educational neuroscience is to conduct constrained experimental research that is theory-driven and yet also clearly related to educators' complex set of questions and concerns. However, the fields of education, cognitive psychology, and neuroscience use different levels of description to characterize human ability. An important advance in research in educational neuroscience would be the identification of a cognitive and neurocognitive framework at a level of description relatively intuitive to educators. I argue that the theory of multiple intelligences (MI; Gardner, 1983), a conception of the mind that motivated a past generation of teachers, may provide such an opportunity. I criticize MI for doing little to clarify for teachers a core misunderstanding, specifically that MI was only an anatomical map of the mind but not a functional theory that detailed how the mind actually processes information. In an attempt to build a "functional MI" theory, I integrate into MI basic principles of cognitive and neural functioning, namely interregional neural facilitation and inhibition. In so doing I hope to forge a path toward constrained experimental research that bears upon teachers' concerns about teaching and learning.

Keywords: functional multiple intelligences, fMI, multiple intelligences, learning, education, cognitive inhibition, educational neuroscience

The nascent field of educational neuroscience challenges scientists to conduct well defined research with relevance to learning processes. However, the fields of education, cognitive psychology, and neuroscience use different levels of description to characterize human ability. In this context it has been relatively difficult to conduct constrained research that remains theory-driven and also maintains its relevance to educators' complex set of concerns.

To this point, researchers and theorists have set forth broad suggestions about how to build the educational neuroscience community. For example, Fischer et al. (2007) have called for "reciprocal interactions" among neuroscience and education. Researchers have been cautioned to pay more than "lip service" to the different levels of description that characterize the different disciplines comprising educational neuroscience (Anderson and Reid, 2009). Many researchers hope for "bilingual" (Byrnes and Fox, 1998; Mason, 2009) or "multilingual" scholars (Ansari and Coch, 2006) engaged in "bidirectional" work (Ansari, 2005; Ansari and Coch, 2006). Szúcs and Goswami (2007) state that merely "sending information across bridges is not the answer" and instead the field needs "a new colony of interdisciplinary researchers."

For the neurocognitive research community, an important step beyond these broad suggestions would be the identification of a cognitive framework at a level of description relatively intuitive to educators. If such a cognitive framework exists, then it may be used to shape educators' questions and concerns into theory-driven, testable neurocognitive research that may advance the education neuroscience field.

In this paper I will suggest that the theory of multiple intelligences (MI; Gardner, 1983), a conception of the mind that motivated a past generation of teachers, may provide cognitive

neuroscientists with a framework in which to conduct rigorous educational neuroscience research. However, I will argue that MI prodded teachers to misconstrue the nature of a scientific theory of cognition; teachers took strongly to MI's value-based claims of the "plurality of intellect," yet largely failed to recognize that MI did not offer a description of how cognitive processes actually operate nor how an individual child's mind learns. Finally, I will attempt to integrate into MI basic principles of cognitive and neural functioning, and in so doing I hope to forge a path toward constrained experimental research that bears upon teachers' concerns about teaching and learning.

ANATOMICAL MODEL vs. FUNCTIONAL THEORY

Gardner (1993) never intended MI to be applied to education. Though it may come as a surprise to many progressive educators, the MI model was created "not as a program for developing a certain kind of mind or nurturing a certain kind of human being," Gardner (1993) has written, but rather to explain "the evolution and topography of the human mind." That is, MI was a map of sorts, seeking to explain what the mind consists of, but not how it works. As such, MI did not address issues critical to the practical and applied needs of educators; beyond recognizing that an intelligence merely exists, MI did not characterize how any one intelligence actually operates, how these intelligences functionally interact with one another, nor how best to teach any one intelligence.

If MI does not, in fact, make any claims about how minds operate nor how to nurture them, what then can explain the affinity educators had for MI immediately upon its introduction in 1983? For space considerations, this question is ultimately beyond the

scope of the current analysis. Yet an important clue may come in Gardner's 1987 suggestion that the "real point here," as he wrote a quarter century ago, "is to make the case for the plurality of intellect." Gardner was motivated by what he saw as a cultural definition of intelligence that was restricted to verbal and logical–mathematical thought alone. If MI did indeed ride a changing socio-cultural wave in a particular era of history, perhaps this explains teachers' strong attraction to the pluralistic values MI put forth. MI's crucial contribution, I believe, was to argue convincingly for the value of kinds of intelligence beyond verbal and logical–mathematical.

Though Gardner considers an intelligence to be an information processing capacity (Gardner and Moran, 2006) MI makes no explicit claims about *how* information is processed. Critically, MI's value-based claims did not necessarily impact how teachers actually taught nor how they understood the neurocognitive processes of learning. By broadening the definition of intelligence, MI may have been a "catalyzing idea" that "let a hundred flowers bloom" (Gardner, 1995). And yet Gardner (1993, 1999) himself has noted that in many ways MI resembles a Rorschach test, and he credits a colleague with the observation that "MI is popular because it does not come with directions. Educators can say they have adopted it without doing anything differently" (Gardner, 2004). By Gardner 's (1993, 1999, 2006) own reckoning, MI did not at its inception, and never has, made any claim about the actual workings of intelligences.

Why is this a problem of great importance to teachers? In starkest terms, MI simply does not explain how children's minds learn. Put differently, positing that eight intelligences exist does not characterize in any way how they process information. For example, MI cannot inform a teacher about whether a child's mathematical–logical intelligence may be nurtured by employing verbal or spatial or kinesthetic intelligence. A teacher with an affinity for MI may indeed view her many students as each having different – and equally valuable – profiles of intelligences. But, critically, this does not provide the teacher insight about whether a child's mind may benefit from engaging one "relatively independent" (Gardner and Moran, 2006) intelligence to facilitate learning in another intelligence; if the intelligences are indeed largely independent, it may be extremely difficult and inefficient to use kinesthetic intelligence, for example, in an instructional activity that aims to improve verbal intelligence. The main point is that MI simply was not built to explain how the mind works – or how it learns. Yet such knowledge is at the heart of instructional decisions teachers must make.

To scientists, the most pressing problem with Gardner's model is equally stark: using classical scientific definitions, the theory of MI is not, in truth, a theory. Scientific theories must make falsifiable predictions about thought and behavior (Schacter et al., 2011). Yet MI "makes no claims" (Gardner, personal communication) about how the mind operates or functions, about whether spatial intelligence supports verbal intelligence, for example. With no specific claims, hypotheses or predictions about cognitive processes to make, constrained experimental research is, simply, impossible. With no experimental research that may prove or disprove it, MI may remain only a "catalyzing idea" (Gardner, 1995), though one that I believe had a profound effect on our culture's

views of intelligence and children. Regardless, from a scientific perspective, MI is not a theory. While this claim may appear abstract and of little practical consequence, it is central to my analysis about how to develop MI such that it becomes a proper scientific theory, one that both is generative for the educational neuroscience community and also one that informs teachers' understanding of learning processes and drives principled, theory-driven instructional decisions.

In sum, two qualitatively distinct propositions have been tremendously conflated in understandings of MI, I argue, a condition that has plagued applications of MI since its inception. On the one hand is a values-based claim, which advocates for making greater efforts to reach the variety of students with different profiles of intelligences that inevitably comprise any teacher's classroom. And, yet, on the other hand is the need for scientifically and empirically derived claims about how the child's mind learns. The following distinction is crucial: assigning value to the different intelligences different students exhibit is fundamentally and qualitatively distinct from the scientific enterprise of characterizing how those intelligences work. Teachers may value all kinds of intelligences; knowing how to teach to and develop them is an entirely different, and critical, endeavor.

In this analysis I define MI as a limited "anatomical" map, reflecting Gardner's (1993) sense that MI was intended to describe the "topography" of the mind. I have belabored the point that MI describes the existence – but not the function – of MI within the mind. In making this distinction I hope to clarify misunderstandings about MI and identify the limits of its scientific reach. Yet in doing so, I hope to advance an argument for how MI may be a suitable framework in which to integrate teachers' questions and concerns with the experimental research methods of cognitive neuroscience.

COGNITIVE PSYCHOLOGY: BUILDING A FUNCTIONAL THEORY OF MULTIPLE INTELLIGENCES

The functional MI (fMI) theory I propose focuses on neurocognitive connectivity. A functional theory will build upon an anatomical or structural map by characterizing the patterns of connectivity among relatively autonomous intelligences.

The fMI theory makes two conceptual moves, one qualitative and one quantitative. First, I ask about the quality, or nature, of the interactions between intelligences: *Are the interactions between any two intelligences facilitatory, inhibitory, or neutral?* Second, I ask about the quantity, or strength, of interactions across intelligences: *Is one intelligence relatively more strongly or weakly connected to other intelligences?* These questions are of practical consequence for effective classroom instruction that is focused on how minds learn.

If each intelligence is "relatively independent yet interacting" (Gardner and Moran, 2006) and subserved by specific neurological structures (Gardner, 1998), then a functional theory would predict that any two intelligences can interact in one of three basic ways. In lay terms we would say they may work together, compete, or be indifferent to each other. I will use the terms facilitation and inhibition to describe the former two, indicating that one intelligence can improve the functioning of another, or that one intelligence can impair another. In neurological

terms we know that, on the very short timescale at which neurons operate, any two brain regions may be connected such that when one region activates it sends an electrical projection to another region that can excite those downstream neurons, or instead can inhibit, or reduce, the electrical firing of those neurons.

What might be the utility of a functional MI theory centered on a facilitation–inhibition connectivity paradigm? In short, it will help us predict whether an instructional activity largely employing one intelligence is likely to improve, or instead impair, ability in another intelligence. For example, research on the phenomenon known as verbal overshadowing (Schooler and Engstler-Schooler, 1990) has shown that people asked to speak about non-verbal experiences (e.g., face recognition or emotions) often perform more poorly on subsequent tests of memory or analysis [for a review, see Cerruti and Wilkey (2011)]. In one study, young children asked to speak about emotions after watching an emotionally disturbing video performed more poorly on a subsequent learning task compared to a control group (Rice et al., 2007). Given especially how much classroom instruction is verbal, teachers will benefit from understanding when employing verbal cognitive processes helps, and when it hinders, the operations of other cognitive processes. In my experience as a middle school teacher over a decade, I observed that teachers very largely assumed that intelligences facilitate one another, but they did not recognize the real possibility that activity in one part of the mind can in fact inhibit another.

A functional MI theory can also help frame functional and structural neurocognitive experiments. Functional magnetic resonance imaging (fMRI) studies can compare activity in occipital regions of the brain dedicated to visualization when a child verbalizes about a visual geometry problem to a no-verbalization condition. Studies of brain structures may avail themselves of a technology such as diffusion tensor imaging (DTI), which measures fractional anisotropy (FA), thought to be a correlate of the extent of myelination in a region and thus an indicator of speed and efficiency of neural connectivity between two brain regions. Higher FA between two regions known to instantiate the core operations of different intelligences would indicate that those intelligences interact relatively strongly. Then, fMRI studies would need to determine whether these interactions are more facilitatory or more inhibitory.

An fMI theory is very well suited to instructional intervention and longitudinal studies. fMRI and DTI may assess changes in response to an intervention in regional activity, functional connectivity, and FA. For example, these technologies can assess whether intense musical training affects activity in core areas that instantiate numerical cognition, as well as myelination between these areas and core musical brain regions.

Moreover, newer technologies may be of potentially great value for examinations of facilitatory and inhibitory connectivity. Transcranial direct current stimulation (tDCS) sends a very mild electrical current between two electrodes placed on the scalp. Depending on where the electrodes are located, different underlying brain regions will be affected, and in this way specific aspects of cognition can be targeted. In my own work I have found intriguing effects, both facilitatory and inhibitory. For example, anodal stimulation, which increases the propensity for neural firing in the affected region, of left prefrontal cortex improved performance on a verbal task with a high working memory load (Cerruti and Schlaug, 2008). In another study, cathodal stimulation, which blocks or inhibits regional activity, of Broca's right-hemisphere homolog in fact improved performance on a task of verbal semantic categorization (Cerruti, 2010). Because verbal ability presumably depends relatively strongly on the left hemisphere, this was interpreted as a disinhibition effect: decreased activity in Broca's right-hemisphere homolog also decreased interhemispheric inhibitory projections, thus permitting increased activity in Broca's. Studies such as this one reveal the complex functional interconnectivity among the multiple regions of the brain that are invariably involved in complex cognition.

CONCLUSION

The purpose of a functional theory of MI is to describe how the mind works. The MI framework was not created with the intention of applying it to education (Gardner, 2006), yet educators took strongly to it. In turn, Gardner (1987, 1991) soon took to advocating for MI-inspired environments in schools. In such environments, MI encourages teachers to value and encourage intelligences other than verbal and mathematical. However, MI is incapable of informing teachers about how the individual child's mind processes information or learns new information.

My analysis has not questioned the anatomical basis of the MI framework. In fact I take as my starting point MI's assumption that the brain is home to relatively autonomous information processing modules. My approach aims only to detail the interactions of cognitive information processing mechanisms. Such an approach owes much to experimental psychology and neurology, fields that have often been critical of MI (Kornhaber and Gardner, 2006).

My core intention is plain: to advance the utility of MI to both teachers and researchers by building a functional theory of MI. I have argued that as the field of educational neuroscience grows MI may be a particularly useful foundation upon which to build a proper scientific theory of neurocognitive learning processes – one that is at a level of description teachers find to be fairly intuitive. For researchers, a functional theory will help organize experimental research in mind, brain, and education, three disciplines that examine cognition and behavior at different levels of description. For teachers, specification of the functional properties of intelligences will help guide instructional decisions about how a child's mind learns.

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