ψ Psychology Press
Taylor & Francis Group

Dynamic Links Between Emerging Cognitive Skills and Brain Processes

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The goal of the present study was to investigate whether advanced cognitive skills in one domain impact the neural processing of unrelated skills in a different cognitive domain. This question is related to the broader issue of how cognitive-neuro-development proceeds as different skills are mastered. To address this goal, event-related brain potentials (ERPs) were used to assess linkages between cognitive skills of preschool children as reflected in their performance on a pre-reading screening test (Get Ready To Read) and their neural responses while engaged in a geometric shape

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matching task. Sixteen children (10 males) participated in this study. The children ranged from 46 to 60 months (SD = 4.36 months). ERPs were recorded using a 128-electrode high-density array while children attended to presentations of matched and mismatched shapes (triangles, circles, or squares). ERPs indicated that children with more advanced pre-reading skills discriminated between matched and mismatched shapes earlier than children with poorer pre-readings skills. The earlier discrimination effect observed in the advanced group was localized over the occipital electrode sites whereas in the Low Group such effects were present over frontal, parietal, and occipital sites. Modeled magnetic resonance images (MRIs) of the ERP component sources identified differences in neural generators between the two groups. Both sets of findings support the hypothesis that processing in a poorer-performing group is more distributed temporally and spatially across the scalp, and reflects the engagement of more distributed brain regions. These findings are seen as support for a theory of neural-cognitive development that is advanced in the present article.

Academic achievement has become a national priority. This priority is strongly stated in No Child Left Behind legislation (2001), which targets growth of reading and mathematics skills, and is also stated in the National Education Goals (1994, 1998), which targeted 2000 as the point when "every child will start school ready to learn." Although most efforts to improve academic achievement have targeted children from kindergarten through grade 12, the focus is expanding to include the preschool period due to increased recognition of the importance of the skills learned by young children for later academic achievement (Whitehurst, 2001). Indeed, findings from national studies (e.g., Denton & West 2002; West, Denton, & Germino-Hausken, 2000) support the consensus statement summarized by Boyer (1991) that children who enter primary school unprepared rarely catch up to their more prepared peers.

No area in preschool education has received more attention than early reading, also known as "emergent literacy," "pre-reading," and "reading readiness." As a result, evidence is accumulating on the cognitive skills that preschool children need to have and to use to in order to become readers by school age. A meta-analysis of studies published through 2003 provides information on predictive relations between early reading skills and skills at school age in word reading, reading comprehension, and spelling (National Early Literacy Panel, 2007). This meta-analysis identified alphabetic knowledge, phonological processing, language, lexical access (rapid automatized naming), and knowledge of print conventions as important precursors of reading skills. However, despite the wealth of information identifying critical cognitive skills that impact reading outcomes and the expansion of states' early learning standards to focus preschool classroom activities on development of these skills (Scott-Little, Kagan, & Frelow, 2003), many children still do not become proficient in these skills during the preschool period. For example, Molfese et al. (2006b) monitored developmental progress of children participating

in pre-kindergarten programs that emphasized early reading skills, including alphabetic knowledge, and monitored developmental progress in these skills across the school year. Fall to spring gains in letter identification were examined and compared with skills in phonological processing, rhyme detection, environmental print and performance on the Get Ready To Read screening test (Whitehurst & Lonigan, 2001). Fifty-three percent of the children who could not identify any letters at pre-kindergarten entry made no gains or gains in recognizing only one additional letter in the spring compared to the 47% of their classmates who made gains averaging 7 letters. In Head Start, which has a comprehensive program designed to address the early educational needs of children from low-income homes, the progress of 3 and 4 year olds in developing emergent literacy and mathematics skills by kindergarten age is below that of all other U.S. children of the same age (Head Start Impact Study, 2005). Understanding why some children make progress in acquiring emergent reading skills while others do not is of central interest to this study.

Our previous work, and that of other researchers, has shown that performance on language and reading tasks can be associated with differences in brain responses to speech sounds at birth and in childhood (Andrews-Espy, Molfese, Molfese, & Modglin, 2001; Benasich, Thomas, Choudhury, & Leppanen, 2002; Guttorm, Leppanen, Poikkeus, Eklund, Lyytinen & Lyytinen, 2005; Guttorm, Leppanen, Richardson, & Lyytinen, 2001; Leppanen, Pihko, Eklund, & Lyytinen, 1999; Leppanen et al., 2002; McBride-Chang, 1996; Molfese, 2000; Molfese & Molfese, 1985, 1997; Pihko et al., 1999). Evidence of these differences is found in neuronal activation patterns reflecting brain processing, both in neuronal circuitry (i.e., anatomy), as well as neuronal signaling (i.e., function; Nunez, 1981; Molfese, Molfese, & Kelly, 2001). Andrews-Espy, Molfese, Molfese, and Modglin (2004) used growth curve analyses to show that it is the development changes in event related potential (ERP) waveform peaks and latencies elicited in response to voiced, bilabial stop consonant-vowel syllables (e.g., /ba, ga/), especially an early occurring negative component, that differentiated the decoding proficiency of 8 year olds. This early component reflected the recruitment of different cortical surfaces or volumes needed to process and use the auditory information that underlies reading skills. Additional support for this hypothesis is provided by recent findings using high density array ERP techniques in which greater amplitude responses distributed over broader brain regions were observed in dyslexic/poor readers compared to average readers while reading a series of consonant-vowel-consonant words, orthographic non-words that were pronounced as words, and pseudowords (Molfese et al., 2006a). Examination of processing efforts reflected in brain responses may offer a way to understand differences between children exhibiting different levels of skill development.

Our view of the implications of these findings builds on a number of positions that have paved the way. Hebb (1949) outlined a widely regarded view of emerg-

ing neural networks that are trained with successive presentations of a stimulus to the point where processing becomes virtually automatic, and subsequently may not require complete exposure to an event in order to be correctly triggered. Parallel and distributed processing approaches reinforced this view (Andersen, 1983; Hinton, Osindero, & Teh, 2006; McClelland & Rumelhart, 1986). One modification that we propose to these views emphasizes the importance of changing spatial and temporal distributions of the brain's neural network with learning. Ultimately, learning and mastery depend on developing stable and rapid temporal links between distributed neural processes. It is our contention that in the early stages of skill acquisition, neural activation is widely distributed across multiple brain sites that communicate with each other initially in a temporally unstable manner and, consequently, inefficient manner. In this phase, the order in which brain areas communicate is continuously in flux. As a skill is mastered, these temporal relationships stabilize. The number of areas engaged decline and begin to stabilize, with the same areas being activated from one time to the next. The order in which these areas communicate also stabilizes with skill mastery. Eventually, maximally efficient processing is carried out by a more restricted set of neural regions that communicate with each other in a temporally stable and predictable fashion.

Data from functional magnetic resonance imaging (fMRI) studies that compare younger with older populations support this view of more focused cortical involvement as development progresses. For example, Casey, Giedd, and Thomas (2000), in an fMRI study of children and adults engaged in memory and attention tasks, note that the magnitude of activity was greater and more diffuse in children relative to adults as indexed by the more extensive volume of activation of the middle frontal gyrus and superior frontal gyrus in children than in adults. In a study of a somewhat older population, Blakemore and Choudhury (2006) also note larger activation patterns in adolescents relative to adults during an emotion task in the regions of the anterior cingulate cortex, the left and right orbital frontal cortex, and the amygdala. Thus, across different tasks and different cortical regions, more cortical areas appear to be activated to a greater extent in younger than older populations. These larger and more diffuse activation patterns in the younger populations occur in spite of the developmental trend in which synaptic and cortical development are increasing with age (Sowell, Trauner, Gamst & Jernigan, 2002; Toga, Thompson, & Sowell, 2006).

We believe that the developmentally changing relationships noted by Casey et al. (2000) and Blakemore and Choudhury (2006) illustrate spatial and temporal neural changes that are critical to the learning process. Initially, acquisition of a skill requires a widely distributed set of neural processes whereby the brain draws on a range of operations. Some of these are more useful than others and weights are assigned to prioritize their processing input relative to other neural contributions. However, these spatial and temporal relationships are unstable in the early stages of learning, some areas are dropped from the developing network while oth-

ers are added. In addition, some areas may be moved temporally forward in the processing sequence, requiring changes in the ways in which these areas communicate spatially and temporally with the old areas they were associated with as well as new areas. Such a distribution of processing across multiple areas with unstable temporal links to each other contributes to the inefficient processing in the early stages of skill acquisition. However, with experience and learning, a more stable network emerges. Neural-functional restructuring moves processing from widely distributed and unstable spatial and temporal networks toward a more stable network composed of areas that relate to each other in relatively fixed, efficient, and predictable ways.

The purpose of the present study was to investigate how the cognitive skills of preschool children are linked to measures of brain-based processing efforts during task performance. More specifically, we examined the relationship between preschool children's literacy/language skills and the organization of the brain in discriminating between shapes during performance on a shape matching task. Although understanding differences between shapes (e.g., a triangle vs. a square) is a component of preschool mathematical knowledge (Starkey, Klein, & Wakeley, 2004), demonstration of this understanding also involves knowledge gained from language and literacy experiences. Indeed, researchers studying preschool children report that mathematics skills load on a common factor with verbal reasoning skills in tests of intelligence (Kline, 1989; Molfese, Yaple, Helwig, Harris & Connell, 1992; Ownby & Carmin, 1988; Thorndike, 1990). High-density ERP techniques were used to measure brain responses of children.

In the present study, it was expected that skills developed in one domain would be reflected in the brain's organization and also impact the brain's organization for another skill. It was hypothesized that children with more advanced language and literacy skills, as indexed by the Get Ready To Read© screening test, would generate ERP components that discriminated between matched and mismatched shapes earlier in time than children with poorer pre-readings skills. Moreover, based on our theory of developing neural organization, it was hypothesized that children with poorer GRTR skills would generate ERPs across more electrode scalp regions and engage more neural structures while discriminating between shapes than children with more advanced GRTR skills. The latter group, because they were expected to have more automated processing, would draw more quickly on fewer neural regions in more effective ways that would project fewer spatial effects to the scalp.

METHODS

The University of Louisville Institutional Review Board approved this study. Parents of participants provided informed consent for the parent/child dyad to participate in the study and each child provided assent to participate.

Participants

Children participating in the study were enrolled in pre-kindergarten programs for economically disadvantaged or developmentally at-risk children in local public schools. District-wide enrollment in these preschool programs was 91% based on family income eligibility. The 16 children included in this study had a mean age of 52.62 months ($SD = 4.36$ months, range 46 to 60 months), with 10 males and 6 females. All were typically developing, with English as a first language, and were distributed across classrooms in 3 schools. The participants' average General Conceptual Ability (GCA) score on the Differential Ability Scales (DAS: Elliott, 1990) was 92.72 ($SD = 15.31$, range = 64 to 119). The range of GCA scores reflect a below average to above average range of scores, a range that we have reported before in studies with children attending public pre-kindergarten programs.

Overall, the 16 children's GRTR scores (number correct) ranged from 5 to 19. For the analyses, they were divided into High and Low ability groups based on median GRTR scores (median = 12). The Low GRTR group had mean GRTR score of 7 ($SD = 1.51$, range = 5 to 9). The High GRTR group had a mean correct score of 16.25 ($SD = 1.49$, range = 15 to 19). However, since a Student paired t-test indicated that the two groups also differed in age, $t(7) = 9.7442$, $p < .0001$, a decision was made to treat age as a covariate in an analysis of covariance.

Measures

Get ready to read. (GRTR; Whitehurst & Lonigan, 2001) is a screening tool designed to measure the emergent reading skills of preschool children. The 20-item assessment includes 4 items related to print knowledge (understanding of books, printed letters, and words), 6 items on emergent writing (text knowledge), and 10 items on phonological awareness (letter sounds, rhyming, segmenting words). The child points to one of four pictures in response to a question. The entire screening tool and technical report are available online (http://www.getreadytoread.org/). The standardization sample of 4 year olds yielded a mean total scale score of 9 with a standard deviation of 4. Split-half reliability was reported by Whitehurst and Lonigan (2001) to be .80 for their sample of 342 4 year olds. The criterion-related validity of GRTR was reported against the *Developing Skills Checklist* (DSC; CTB/McGraw-Hill, 1990). The correlation between GRTR and DSC for children from low-income families (Head Start) was .70, and the correlation for children from middle-income homes was .79 for the standardization sample.

ERP measures of shape matching. A Shape-Matching Task was used to elicit event-related potential responses. The visual stimuli included pictures of two shapes of the same color, presented two at a time. The shapes included three stan-

dard geometric shapes, a circle, square, and an equilateral triangle. The sides of the square and triangle were of equal length. The shapes were uniformly colored in red, blue, green, or yellow, with all colors occurring equally often across the test session.

Screening tests.   Children included in the analyses passed several screening tests. A visual assessment was used to screen for visual acuity. This procedure required children to stand 10 feet away from a "*Tumbling E*." Children were asked to cover their left eye with their left hand and use their right hand to indicate the direction of the letter "E" by pointing to the left, right, up, or down. The same procedure was then used for the left eye in which the right hand covered the right eye and children pointed with their left hand. Each child included in this study demonstrated at least 20/30 visual acuity in both eyes. A 10-item neuropsychological assessment was used to screen children for neuropsychological risk factors. Parents were asked "yes/no" questions with regard to their child having had prior head injuries, prenatal complications, low birth weight, or complications in educational, medical and/or neurological domains. If parents indicated "yes" to any of the questions, children were excluded from subsequent analyses. All children used their right hand to perform most tasks on the Edinburgh Handedness Inventory (Oldfield, 1970) (mean Laterality Quotient = .58, *SD* = .27, range = .09 to 1.0).

Procedures

In the fall of the school year, parents of potential participants were sent information regarding a behavioral study of literacy and mathematics skills. Parents returned signed consent forms and demographic information sheets. Children participating in this study were involved in a larger study involving language and early reading and mathematics assessments given in two sessions at their preschools: one in the fall and one in the spring. Parents were contacted to obtain permission for their child to participate in a third session that took place in the summer. The DAS was administered in the fall session, and the GRTR was administered in the spring. Each session in the school year took approximately 15–30 minutes to complete. During the summer session, the screening and handedness tests were administered followed by the ERP assessments. This session lasted approximately 55 minutes, with short breaks from testing distributed throughout the testing period.

For the ERP session, children were tested individually in a sound-attenuated testing room. Prior to the experiment, the child was familiarized with the testing room. Once the child was seated comfortably, his/her head was measured to determine the appropriate electrode net size and the two reference points (Cz, a mid-central position at the top of the head, Fz, and the nasion, a position central at the top of the bridge of the nose) in order to assist in aligning the electrode net when it was placed on the child's head.

Following net application, the child was instructed to sit quietly and to view the items displayed on a high-resolution monitor positioned 1 m in front of the child at eye level. Sixty same shape pairs (match condition) and 60 different shape pairs (mismatch) were presented in random order to each child. Each stimulus was presented for 1 Sec followed by a varied ISI from 4 to 6 Sec before the next stimulus was presented. The children were instructed to press one button if the two shapes on the screen were identical and a second button if the shapes were different. Stimulus presentation was controlled by the Electrophysiological Graphical Imaging System (EGIS), v. 2.2 (EGI, Inc.). During stimulus presentation, the child's EEG and EMG as well as behavioral observations were continuously monitored. During periods of motor activity or inattention, stimulus presentation was suspended. Testing was resumed when the child's alertness and motor activity returned to an acceptable level.

The brainwaves were recorded using a high-density array of 128 Ag/AgCl electrodes embedded in soft sponges and arranged into a net (Geodesic Sensor Net, EGI Inc.). During recording, all electrodes were referenced to Cz and then subsequently re-referenced to an average reference during data analysis. All impedances remained at or below 40 kOhms throughout the test session as indicated by measures taken before and after the stimulus presentation period. The high-pass filter was set to 0.1 Hz and the low-pass to 30 Hz.

Net Station 2.0 (EGI, Inc.) was used to record the electrophysiological data with the sampling rate set to 250 samples/Sec Subsequent analyses focused on the 500-msec period immediately following stimulus onset, a time frame selected based on previous work with a similar age population. Children received small gifts after completing the test sessions.

RESULTS

The ERP data from all participants were digitized at 4 msec intervals and then segmented to include a 100-msec pre-stimulus interval (baseline) and a 900-msec post-stimulus interval. Prior to the statistical analyses the data were re-referenced to the average of all electrodes. The segmented data then were averaged individually for each participant in that artifact rejection was carried out on the ERP data for each electrode to eliminate ERPs contaminated by motor movements and eye artifacts from further analysis. If an artifact (operationally defined as a shift in the voltage level in excess of 100 µV) occurred on any one electrode channel during the 100 msec pre- or 900 msec post-stimulus period on any trial, all of the ERPs collected across all of the electrode sites for that trial were discarded from subsequent analyses. Rejection rates were comparable across GRTR groups and stimulus conditions. Electrodes identified as "bad" (poor signal quality on 10% or more of the trials) were replaced by interpolating their data from immediately adjacent

electrodes. The remaining clean trials were averaged individually for each condition and participant and then baseline corrected. Next, all data from individual electrodes were averaged within each of ten scalp regions (five scalp regions for each hemisphere—frontal, central, parietal, occipital, and temporal). This approach represented a modification of the clusters proposed by Curran (1999), but altered such that the average of the 10 regions equaled zero. The purpose of the clustering procedure was to reduce the number of variables (i.e., reduce 128 electrode sites to 10 electrode regions) in order to increase statistical power. The group averaged visual ERPs elicited during the shape matching task are displayed in Figures 1 and 2.

The analyses involved several steps. First, the first 500 msec of the ERP following stimulus onset for each of the 320 averaged ERPs (16 children × 2 stimulus conditions × 10 scalp regions) were submitted to a temporal Principal Components Analysis (PCA) in which the 125 time points (sampled at 4 msec intervals) were treated as variables whereas the individual ERPs were treated as cases. A series of orthogonally rotated factors (using Varimax rotation) identified regions of variability within the 500-msec post stimulus interval. A Scree test (Cattell, 1966) identified the number of factors for subsequent analyses. As noted earlier, because a Student paired t-test indicated that the two groups differed in age, age was treated as a covariate in all subsequent analyses. Consequently, the factor scores (weights) from the PCA were submitted to an Analysis
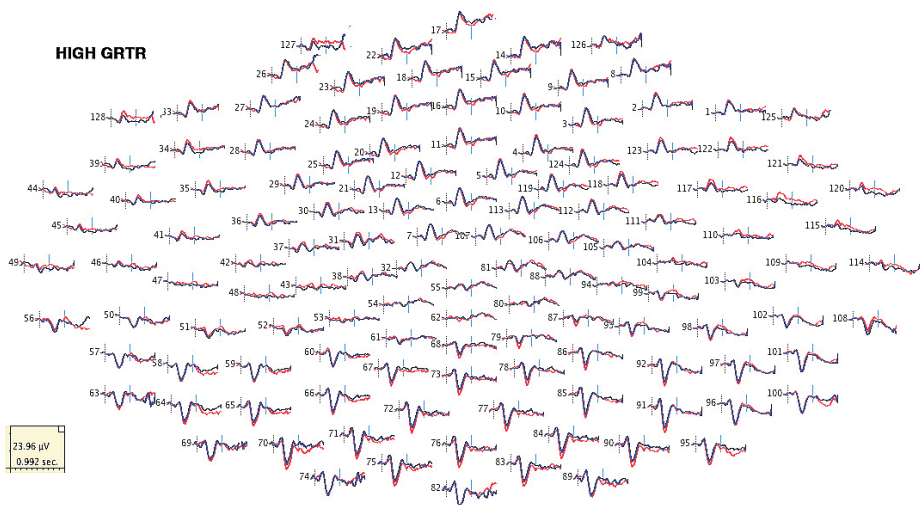

FIGURE 1   Group averaged ERP recordings from the HIGH GRTR Group elicited in response to the MATCH (BLUE) and MISMATCH (RED) trials from 128 electrode high density array. Average reference. Positive is up. Time course is 1,000 msec.
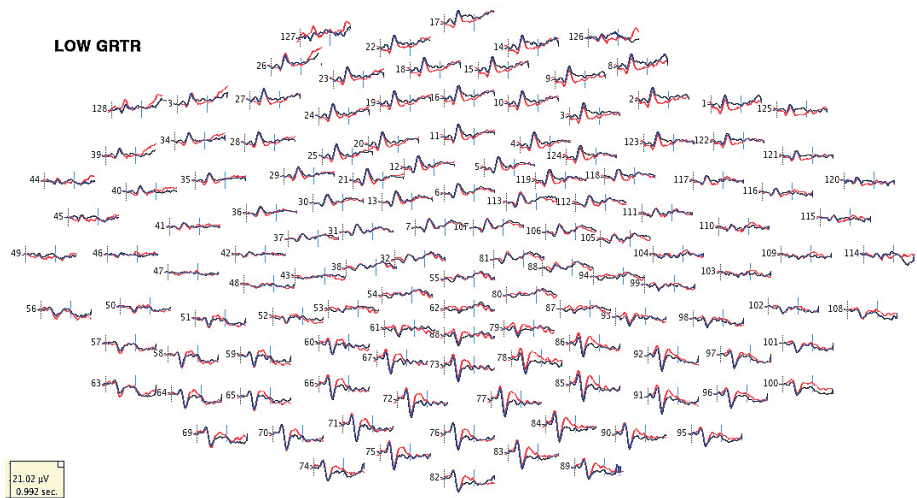
FIGURE 2   Group averaged ERP recordings from the LOW GRTR Group elicited in response to the MATCH (BLUE) and MISMATCH (RED) trials from 128 electrode high density array. Average reference. Positive is up. Time course is 1,000 msec.

of Covariance (ANCOVA) to identify the sources of the variability in the ERPs. The ANCOVA design included a between groups factor for Pre-Reading GRTR Group (2: High GRTR, Low GRTR) and repeated measures for Stimulus Category (2: Match, Mismatch) × Electrode Region (5: frontal, central, parietal, occipital, and temporal) × Hemispheres (2: left, right) using the Greenhouse-Geisser correction. A Tukey HSD was calculated to disambiguate significant interactions. These procedures directly addressed the question of whether ERP waveforms at different electrode sites and latencies (the temporal factors determined by PCA) differed systematically between the different GRTR Groups and match categories.

This analysis approach has proven successful both in identifying ERP regions where most of the variability occurred, and subsequently in determining if the variability characterized by the different PCA extracted factors results from systematic changes in the independent variables under investigation (Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982). When questions are raised regarding misallocation of variance in a PCA analysis across immediately adjacent peaks, Wood and McCarthy (1984) noted that traditional amplitude and latency approaches are as "subject to the problem of component overlap" (see also Chapman & McCrary, 1995, p. 258; see also Beaducel & Debener, 2003, p. 112, regarding analysis power). Given our current power estimates, we considered the PCA approach reasonable for the present investigation.

PCA Results

Three major peaks were clearly observed in the average ERP across the sample over anterior scalp regions, an initial positive peak that reached its maximum positive value at 128 msec (P128), a subsequent large negative peak at 224 msec (N224), a later occurring positive peak at 352 msec (P352), that is then followed by a small positive plateau at 480 msec that interrupts briefly a slow negative going shift in polarity that continued to the end of the data window. The temporal PCA characterized the variance in the data set with three factors, each of which was composed of 125 factor loadings (4 msec samples over a 500 msec epoch), whose values corresponded to the variability characterized by that factor for three specific time regions of the ERP. The first factor (Factor 1) accounted for 37.67% of the total variance. It characterized a late slow wave that began approximately 264 msec post stimulus onset, peaked at 368 msec, and slowly declined through 500 msec the end of the analysis window over posterior electrode sites while increasing steadily over anterior electrode sites. Factor 2 accounted for 21.12% of the variance, and reflected increasing variance between 168 and 264 msec, with peak variance reached 192 msec following stimulus onset. This component appeared to capture the variability in the ERP waveform surrounding an earlier occurring major peak with a latency of 224 msec. This component appears as a positive peak over anterior electrode sites and a large negative peak of a similar latency over posterior sites. Factor 3 (20.86% of total variance) captured a region of variability that extended from stimulus onset until 160 msec (peak = 48 msec) and captured the variance associated with the initial peak that reached its maximum at approximately 128 msec.

ANCOVA Results

All results are presented in the temporal order in which they occurred following stimulus onset. Effects reported focus on GRTR Group and shape match versus mismatch trials.

Main effects for GRTR group, $F(1,13) = 12.59$, $p < .004$, observed power = .91, Electrode Regions, $F(1.35, 17.56) = 10.31$, $p < .003$, observed power = .92, and an interaction for GRTR Group $\times$ Match $\times$ Electrode $\times$ Hemisphere, $F(2.68,34.88) = 4.78$, $p < .009$, observed power = .838, were found for Factor 2, the region overlapping the N224 component. As indicated in Table 1, analyses of the four-way interaction indicated that in both groups of children, the anterior electrode sites differed from posterior sites during match versus mismatch trials. Only one regional difference occurred between the two groups where ERPs from the High GRTR group discriminated match from mismatch conditions at central versus temporal sites whereas no such differences were noted at these sites for the Low GRTR group.

In the next temporal portion of the ERP, a series of interactions involving GRTR group effects occurred between 264 and 500 msec, as captured by Factor 1. Two

TABLE 1
Match–Mismatch Contrasts

High GRTR	T =	p-level	Low GRTR	T =	p-level
LF LT	3.199	0.0064	LF LT	2.3614	0.0332
RF RT	3.0954	0.0079	RF RT	1.5951	ns
LF LC	0.4818	ns	LF LC	1.0754	ns
RF RC	1.0891	ns	RF RC	0.7446	ns
LF LP	4.2115	0.0009	LF LP	3.9501	0.0015
RF RP	4.6641	0.0004	RF RP	3.545	0.0032
LF LO	4.2077	0.0009	LF LO	5.5042	0.0001
RF RO	4.5983	0.0004	RF RO	5.51	0.0001
LC LT	3.553	0.0032	LC LT	1.8109	ns
RC RT	3.4666	0.0038	RC RT	1.3045	ns
LC LT	3.553	0.0032	LC LT	2.837	0.0132
RC RT	3.4666	0.0038	RC RT	4.3211	0.0007
LC LP	4.6775	0.0004	LC LP	4.6775	0.0004
RC RP	4.9347	0.0002	RC RP	4.7126	0.0003
LT LO	2.7505	0.0156	LT LO	3.592	0.0029
RT RO	3.0354	0.0089	RT RO	3.4672	0.0038
LT LP	2.1856	0.0463	LT LP	0.0801	ns
RT RP	2.6603	0.0186	RT RP	2.5037	0.0253

LF = Left Frontal RegionLP = Left Parietal Region
RF = Right Frontal RegionRP = Right Parietal Region
LC = Left Central RegionLO = Left Occipital Region
RC = Right Central RegionRO = Right Occipital Region
LT = Left Temporal Region
RT = Right Temporal Regionns = non-significant

interactions were noted: a GRTR Group × Match interaction, $F(1,13) = 5.18$, $p <$ .04, observed power = .56, and a GRTR Group × Match × Electrode interaction, $F(1.34,17.40) = 7.20$, $p < .01$, observed power = .99. This region of variability in the ERP overlapped the second large positive component, N352, over anterior sites and a small positive peak (P352) over posterior electrode sites.

An examination of the Group × Match × Electrode interaction indicated that the Low GRTR Group discriminated between the Match and Mismatch conditions at frontal electrode sites, Tukey's HSD (q) = 3.2418, $p < .05$, parietal sites, Tukey's HSD (q) = 4.631, $p < .01$, and occipital sites, Tukey's HSD (q) = –8.5677, $p < .01$.

Only ERPs recorded over the occipital region discriminated match from mismatch trials for the High GRTR group, Tukey's HSD (q) = 5.0943, $p < .01$.

The GRTR Group effects identified in the interactions can be seen in the group averaged ERPs for the High and Low GRTR children depicted in Figure 3. Averaged ERPs for the High and Low GRTR groups for Electrode 11 (a midline frontal electrode site) are depicted at the top of the figure for the High and Low GRTR groups. ERPs recorded from a posterior electrode site over the occipital scalp region are represented by Electrode 68 (a midline occipital electrode) displayed in the lower portion of the figure. The ERPs recorded from the High GRTR group discriminated between the match and mismatch conditions during the early region labeled "F2" that occurred between 168 msec and 264 msec. The ERPs from the Low GRTR group discriminated between the match and mismatch conditions during this same time period and during at a later time period (248 to 496 msec). Amplitude variations for the two GRTR groups across the 128 electrode sites are displayed in the topographic maps depicted in Figures 1 and 2 as well as the amplitude topographic maps depicted in Figure 4.
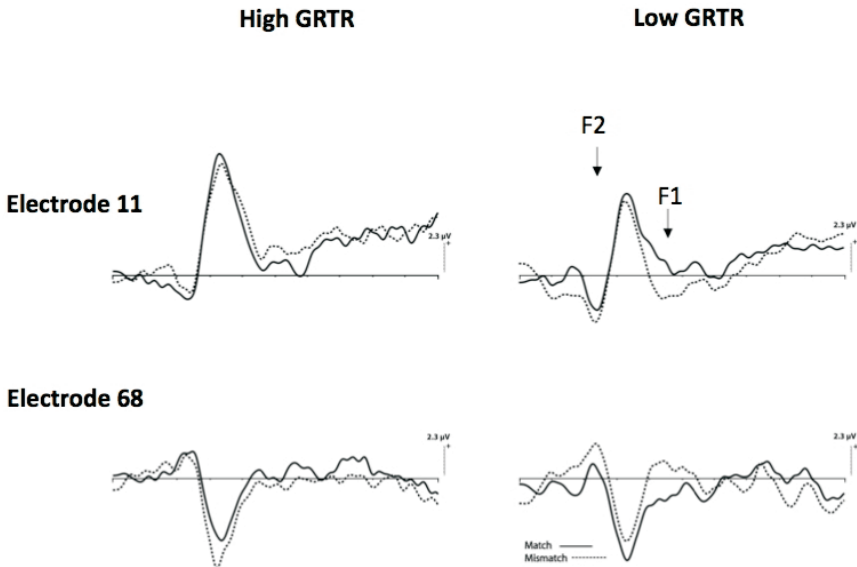

FIGURE 3   ERP recordings from a frontal midline electrode site (E11) are at the top of the figure and those from a midline occipital site (E68) are at the bottom. Solid lines indicate ERPs to the Match condition whereas dotted lines indicate responses to the Mismatch condition. The arrows labeled "F1" and "F2" indicate regions of the ERPs characterized by the PCA derived factors that mapped onto GROUP and MATCH versus MISMATCH differences. ERPs from both groups differed between Match and Mismatch trials only between electrode sites. Duration is 1,000 msec and includes the 100 msec prestimulus period. Vertical time markers are at 100 msec intervals. Calibration is 2.3 μV with positive up.
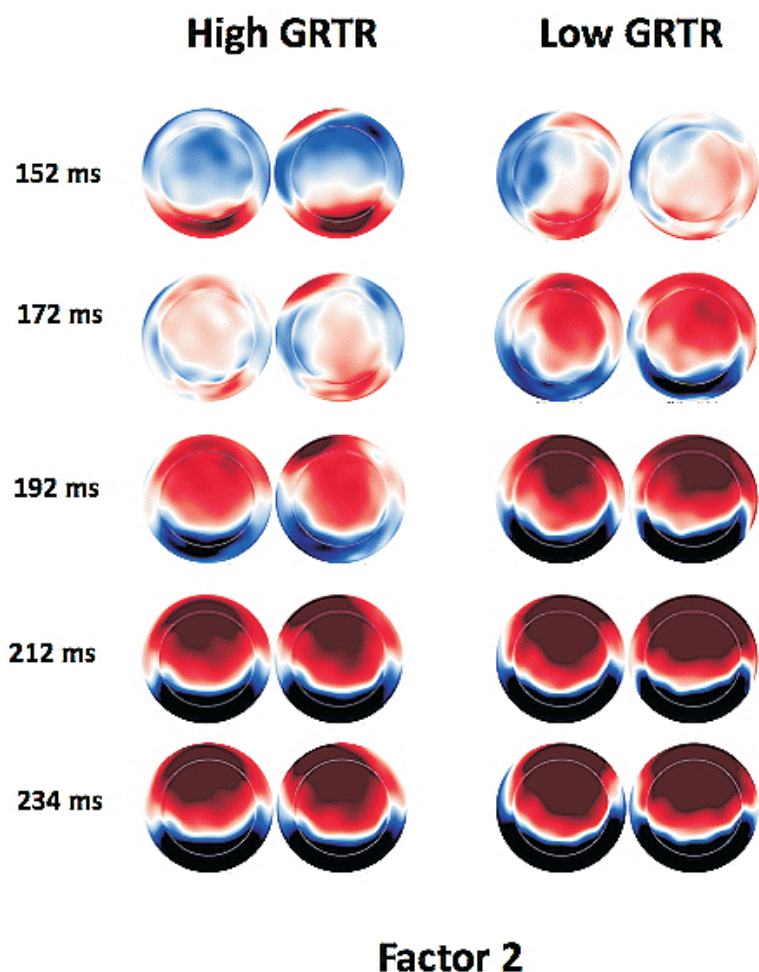
FIGURE 4   A time series for Factor 2 represents pairs of scalp topographies for the MATCH
(left side of the pair) and MISMATCH (right side of the pair) conditions for 20 msec intervals
that bracket the peak latencies for Factors 1 and 2. The voltage calibration marker on the top
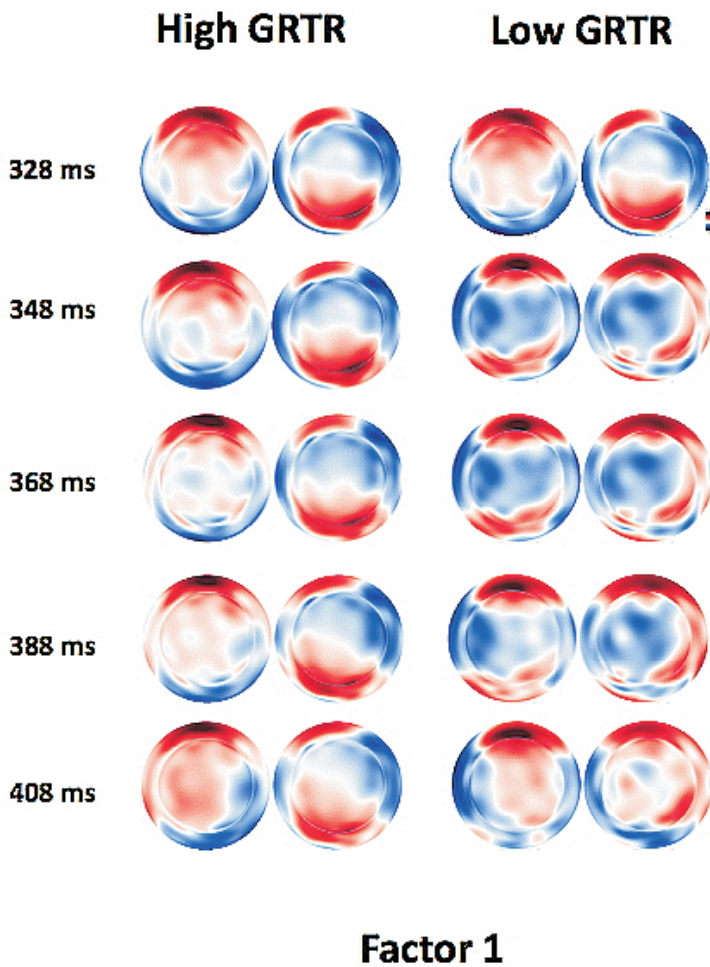right set of scalp topographies ranges from –5 μV to +5μV.

FIGURE 4   *(Continued).*

Source Localization

This final step of the analyses focused on brain source estimates of the neural sources responsible for generating the scalp recorded ERPs that varied between the GRTR groups, stimulus conditions and electrode sites. To accomplish this goal, the averaged ERP data for each GRTR Group were input in separate analyses as variables into a source localization software program (Geosource©, EGI, Eugene, OR,). Geosource© used a Finite Difference Model (FDM) for Inverse Modeling in which a Minimum Norm Least Squares (MNLS) solution was sought to more ac-

curately compute the lead field in relation to head tissues, where the skull is the principal resistive component. The FDM allows accurate characterization of the cranial orifices, primarily the optical canals and foramen magnum. This Model uses the Montreal Neurological Institute (MNI) database for estimating its geometrical constraints. FDM used information from the database, that includes 198 participant brains, used to calculate the position of dipoles within the brain in an attempt to determine the points of origin for the scalp recorded ERPs. From these 198 brains, an average brain was calculated and an individual with this typical brain was scanned using CT and MRI imagers in order to create the geometry that constrains the FDM. The cortex is characterized by the gray matter voxels of the Montreal Neurologic Institute average MRI, thereby approximating the cortical location for individual subjects. A regional dipole triple (comprising dipoles in the x, y, and z orientations) was assigned to each of the 2,394 cortex voxels of this average MRI with Talariach registration. The tissue volumes were parceled using 2-mm voxels to form the computational elements of the FDM. Conductivity values used in the FDM model include: 0.25 S/m (Siemens/meter) for brain, 1.8 S/m for cerebral spinal fluid, 0.018 S/m for skull, and 0.44 S/m for scalp (see Ferree et al., 2000). These values are based on recent reports that the skull-to-brain conductivity ratio is approximately 1:14 (Ryynanen Hyttinen, Malmivuo, 2006). Weighting was placed equally across locations with regularization carried out via TSVD (1×10^{-3}) using LAURA (local autoregressive average) as a constraint (Grave de Peralta Menendez, Murray, Michel, Martuzzi, & Gonzalez Andino, 2004). The Radius of influence was set to 12.2 mm with an exponent equal to 3.

One cautionary note is important. The MNI database is based on adults as are virtually all software-based source analysis programs. In utilizing GeoSource to isolate neural sources in preschool children, we recognize that the source models invariably must be subject to some error. Child brain size and level of maturation for cortical structures in terms of neurogenesis and myelination will differ from adults as outlined in the introduction, although by 5 years of age the size and state of the brain begins to approach that of the adult. However, we expected that the error was constant when applied to this population. Source differences between the GRTR Groups should reflect at some level differences in the pattern of neural structures activated.

Figure 5 includes the modeled MRIs with source regions of interest (ROI) based on modeling the 128-electrode high density array data. In the case of the High GRTR group in the Match condition, maximum activation at 192 ms occurred bilaterally in the amygdala gyrus of the Limbic Lobe with some slightly higher activation in the right hemisphere. Processing of mismatch information activates more posterior regions involving the posterior area of the cingulate (Brodmann Area 31). In contrast, the Low GRTR children appear to activate the medial portion of the parietal lobe in the area of the precuneus (Brodmann Area 17) and middle temporal gyrii (Brodmann Area 31) when viewing matching shapes but
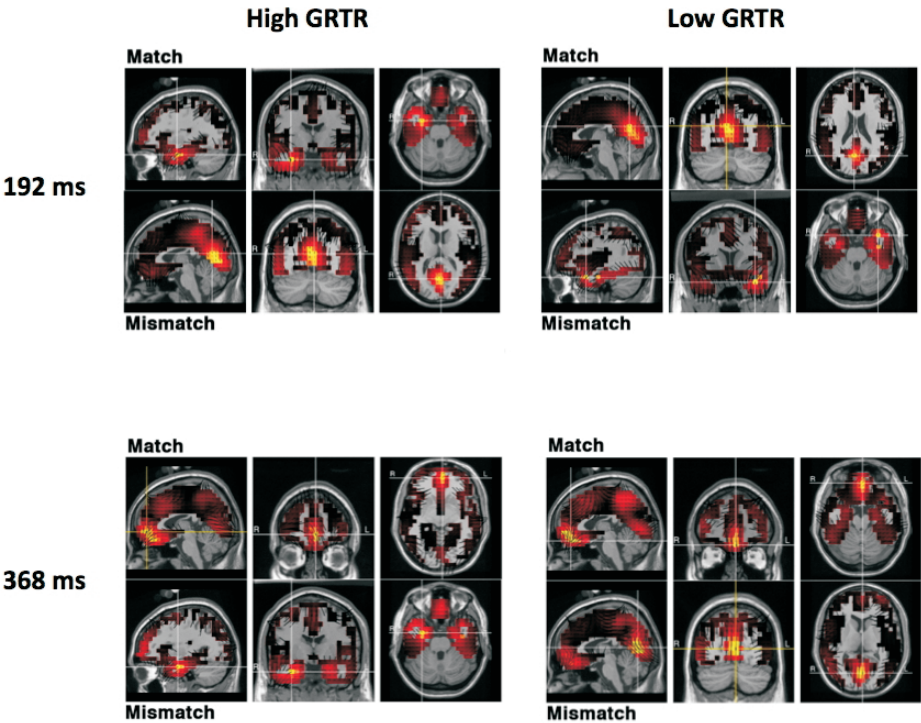
FIGURE 5   Modeled MRIs with source regions of interest based on modeling the 128-electrode high-density array data. The modeled MRIs for the HIGH GRTR Group are displayed on the left side of the figure whereas those for the LOW GRTR Group are shown on the right. Modeled MRIs for 192 msec are depicted at the top of the figure whereas those for the 368 msec period are displayed at the bottom. Within each set of Modeled MRIs, the match response activations during the Match condition are presented from left to right in sets of three whereas those for the Mismatch condition are presented immediately under the first. The three MRI pictures for each set depict from left to right the sagittal, coronal, and axial sections of the brain at the point of maximal activation (indicated also by the yellow cross-hairs). Yellow areas indicate points of highest activation, with lesser levels of activation in red. The left hemisphere is presented on the right side of each modeled MRI whereas the right hemisphere is depicted on the left following standard radiological convention.

then activate the superior temporal gyrus of the Temporal Lobe (Brodmann Area 38), the orbital gyrus of the frontal lobe (Brodmann Area 11), and the inferior parietal lobe (Brodmann Area 40) when the shapes do not match.

In examining the temporal region identified by Factor 1 that was maximal at 368 msec, GeoSource© modeling indicated that the High GRTR group activated the medial frontal gyrus of the frontal lobe (Brodmann Area 10) during match trials but this activation shifted during mismatch trials bilaterally to the amygdala gyrus of the limbic lobe. The Low GRTR group also shows frontal activation dur-

ing match trials, but more inferior to the High GRTR group, with activation of the orbital gyrus (Brodmann Area 11), as well as a lower level of activation in the medial frontal gyrus (Brodmann Area 10) and the precuneus lobe (Brodmann Area 17). Although mismatch trials continue to show some activation in the orbital gyrus, maximum activation occurred in the cuneus lobe of the Occipital Lobe (Brodmann Area 23). The activated areas for the two groups of children for the two time periods are summarized in Table 2.

DISCUSSION

The present study investigated the relationship between brain and skill development. Performance on a screening test for pre-reading skills was linked to brain processing time (latency) and brain organization (spatial distribution) measured during performance on a shape matching task. It was expected that when skills in one domain are well developed, the organization of the brain would differ from those who with poorer developed skills. This hypothesis was supported. We found that children with both high and low pre-reading skills as indexed by the GRTR screening test generated ERP responses reflecting discriminations between matched and mismatched shapes. However, these responses differed in time for children with High GRTR scores compared to children with Low GRTR scores. As noted in the results and viewed in Figure 3, two regions of the ERP varied as a

TABLE 2
Activation Areas Identified Using Geosource© for the High and Low GRTR
Groups for the Two ERP Temporal Regions Sensitive to Group Differences

| Latency | High GRTR | | Low GRTR | |
	Match	*Mismatch*	*Match*	*Mismatch*
192 msec	Bilateral Amygdala Gyrii	Posterior Cingulate B31	Precuneus Lobe B17 Middle Temporal Lobe B31	Bilateral Superior Temporal B38 Orbital Frontal Gyrus B11 Inferior Parietal Lobe B40
368 msec	Medial Frontal B10	Bilateral Amygdala Gyrii	Orbital Gyrus, B11 Medial Frontal Gyrus B10 Precuneus Lobe B17	Cuneus Lobe B23 Orbital Gyrus, B11

B = Brodmann Area.

function of shape match versus shape mismatch trials. For the first of these that peaked at 192 msec and contributed to the negative-positive shift from 168 to 264 msec, the N150–P224 peak complex (Factor 2), ERPs recorded from both groups of children discriminated match versus mismatch trials. In a subsequent ERP region that overlapped the P352 component (Factor 1), the Low GRTR Group discriminated between the Match and Mismatch conditions across multiple scalp regions that included the frontal, parietal and occipital regions. In contrast, ERP responses from the High GRTR group only differed over the occipital electrodes. Thus, ERP responses from the Low GRTR Group differentiated between the match and mismatch conditions across two temporal regions while the level of activity for the High Group was greatly reduced during this second time period, suggesting that processing was more complete and required less later effort for the High GRTR group.

 In general, earlier processing as indexed by shorter ERP component latencies, is associated with more experience, more advanced abilities, and skill mastery. For example, Molfese and colleagues (2006b) reported that children reading two years beyond their expected levels processed three letter words 100 ms faster than same-aged children who were two years behind in their reading skills (see also Holcomb, Ackerman, and Dykman, 1985, and Taylor and Keenan, 1990, who report similar latency differences). In the current study children with better mastery of pre-reading skills (the High GRTR Group) generated ERPs discriminating between conditions over only one electrode regions later in the waveform while the Low GRTR group showed such activity over three regions.

The results of the Geosource analyses reinforce the notion that processing effort was reduced in the High GRTR Group. With the exception of activating the medial frontal gyrus during matching trials late in the ERP (368 msec), the High and Low GRTR Groups differed in the areas activated during match and mismatch trials across the two latencies studied. Moreover, the Low GRTR Group activated reliably one to two more areas during both match and mismatch trials. We interpret these findings to indicate that there were marked differences in brain organization between these two groups of children and that the Low GRTR Group had to engage more areas in order to process the same information as the High GRTR Group.

We believe that differences in the types and numbers of brain areas activated as well as the reduced level of activation later in time by the High GRTR Group resulted from the pre-reading skill development that facilitated the rapid and more spatially limited processing of information in a second domain. With the development of neural processes that support one set of skills, changes in the brain's overall organization invariably must impact the manner in which the brain subsequently acquires and organizes other skills. This applies to cases even where the processing demands and skills may represent related but not the identi-

cal domains, as in the present case of pre-reading skills and geometric shape matching.

The scalp distributions further reflect the difference between the two GRTR groups in discriminating between the matched versus mismatched shapes. The later discriminations made by the High GRTR Group were restricted to the area over the occipital electrode sites while the discriminations made by the Low GRTR Group were more distributed, occurring over frontal, parietal and occipital sites. This last point is relevant to the second hypothesis—that processing in the poorer performing GRTR group is more distributed across the scalp, perhaps reflecting the engagement of more diverse or distributed brain regions. Given this line of reasoning, based on the distributed scalp effects, it appears that the processing of the shape information is more efficient in both the recruitment of brain areas and the speed of processing for the High GRTR Group. Children with more advanced skills may already have automated their processing to a point that it draws on fewer neural regions in more effective and rapid ways, perhaps by using more stable networks. Consequently, processing may be completed earlier or completed at the same time but using fewer resources. Interestingly, Pugh et al. (2000) note in studies using fMRI that reading disabled readers, relative to non-impaired readers, exhibit increased activation of both the inferior frontal and right hemisphere posterior regions. Although Pugh et al. (2000) speculate that this increased frontal activation occurs in order to compensate for left hemisphere posterior processing problems, we suggest that the neural network is more poorly defined in this population and that the reading impairment in part arises from their attempts to utilize more disparate spatial areas when attempting to process similar information.

The fact that different ERP components discriminated between the Match and Mismatch conditions for the High versus Low GRTR Groups provides another point to support our view that different neural substrates are engaged in processing between the two GRTR groups. Across the literature, different ERP components generally map onto different cortical elements, depending on stimulus and task factors (Key, Dove, & Mcguire, 2005). In adults, the visual N1 amplitude is usually largest over the occipital region (Hopf, Vogel, Woodman, Heinze, & Luck, 2002) or the inferior temporal regions (Bokura, Yamaguchi, & Kobayashi, 2001), and typically larger during stimulus discrimination tasks when participants attend more to specific stimulus features. Converging findings from MEG, ERP, and MRI suggest that the likely sources for the visual N1 reside in the inferior occipital lobe and the occipitotemporal junction, with additional sources within the inferior temporal lobe (Bokura et al., 2001). In the case of our Low GRTR Group, however, additional scalp distributions indexing more stimulus discriminations occurred over the next 300 msec and were present over occipital as well as frontal and parietal electrode sites, suggesting that other neural sources contributed to task perfor-

mance in the case of the Low GRTR Group. Previous studies of the N2 component noted that stimulus discrimination does produce changes in its amplitude (Satterfield, Schell, Nicholas, Satterfield, & Freese, 1990). Using intracranial electrodes placed directly on the cortex, Allison, et al. (1999) observed that letter-strings of recognizable nouns produced a N2 component at the fourth occipital gyrus near the occipitotemporal sulci. Pictures of complex objects, such as cars and butterflies, resulted in an N2 response over the inferior lingual gyrus medially and the middle occipital gyrus laterally.

These data are consistent with the theoretical perspective advanced earlier in this article. During acquisition of a skill, neural activation is widely distributed across multiple brain sites that communicate with each other initially in a temporally unstable manner. In this phase, the order in which brain areas communicate is continuously in flux, with one area activating first upon representation of a stimulus while on the next trial a different area may be initially activated and followed temporally and spatially by yet a third area. From trial to trial, the order in which different areas are activated would also shift. However, as a skill matures, these spatial and temporal relationships and the order in which such areas communicate begin to stabilize while the number of involved areas declines. As a consequence, processing becomes more efficient and faster as fewer neural regions are engaged and as the temporal order stabilizes and becomes more routine.

These findings are important not only for contributing to a better understanding brain–behavior relations, but also to providing information useful for the education and intervention communities seeking to understand and address individuals differences in acquiring key cognitive skills, such as reading and mathematics. While cognitive skill domains have become incorporated into the Early Learning Standards adopted by states in response to the National Education Goals (1994, 1998), the integrated nature of these domains has been emphasized. Understanding that cognitive skills interact and facilitate development between and within skill domains is important, and seeing the different degrees of integration as reflected in scalp topographic maps and modeled MRI may provide other ways to understand such findings.

ACKNOWLEDGEMENTS

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