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Real-time Tracking of Motor Response Activation and Response Competition in a Stroop Task in Young Children: A Lateralized Readiness Potential Study

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Abstract

■ The ability to select an appropriate motor response by resolving competition among alternative responses plays a major role in cognitive performance. fMRI studies suggest that the development of this skill is related to the maturation of the frontal cortex that underlies the improvement of motor inhibition abilities. However, fMRI cannot characterize the temporal properties of motor response competition and motor activation in general. We studied the development of the time course of resolving motor response competition. To this end, we used the lateralized readiness potential (LRP), an ERP measure, for tracking correct and incorrect motor cortex activation in children in real time. Fourteen children and 14 adults took part in an animal-size Stroop task where they selected between two animals, presented simultaneously on the computer screen, which was larger in real life. In the incongruent condition, the LRP detected stronger and longer lasting incorrect response activation in children than in adults. LRP results could explain behavioral congruency effects, the generally longer RT in children than in adults and the larger congruency effect in children than in adults. In contrast, the peak latency of ERP waves, usually associated with stimulus processing speed, could explain neither of the above effects. We conclude that the development of resolving motor response competition, relying on motor inhibition skills, is a crucial factor in child development. Our study demonstrates that the LRP is an excellent tool for studying motor activation in children. ■

INTRODUCTION

Our environment is full of relevant and irrelevant stimuli that potentially affect behavior. It is a major task for our nervous system to continuously monitor the environment, to select relevant stimuli, and to adjust behavior according to these stimuli while simultaneously neglecting irrelevant stimuli and suppressing behavior elicited by these stimuli. Most probably, relevant and irrelevant stimuli are processed in parallel, and if their processing speed is comparable, they may activate motor response processes in parallel (Smid, Mulder, & Mulder, 1990; Gratton, Coles, Sirevaag, Eriksen, & Donchin, 1988; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985; Eriksen, Coles, Morris, & O'Hara, 1985; Eriksen & Schultz, 1979; Eriksen & Eriksen, 1974). If different stimuli or different aspects of the same stimuli activate opposing behaviors at the same time, then response competition occurs which the organism must overcome to function effectively (Posner & Snyder, 1975; Morton & Chambers, 1973). Behavioral evidence suggests that the ability to resolve response competition enhances with age. Clearly, this is an important developmental achievement and has a significant effect on performance of cognitive tasks (Ridderinkhof & van der Molen, 1995, 1997). Here, our objective was to use an ERP measure for tracking and comparing the time course of overcoming response competition in children and adults.

We have used a Stroop task for studying the time course of resolving motor response competition. In Stroop tasks, a stimulus has at least two different dimensions. Participants have to respond according to one dimension while neglecting the other dimension. Performance is worse when there is a conflict between the task-relevant and the task-irrelevant dimensions. This is taken to indicate that the task-irrelevant dimension has been processed. For example, in the original color–word Stroop task, participants have to name the color of the ink in which a color word is printed (Stroop, 1935). Performance is faster and more accurate when the ink color matches the meaning of the word (e.g., "red" printed in red ink) than when the ink color does not match the meaning of the word (e.g., "red" printed in blue ink). According to the major theories of the Stroop effect, the Stroop conflict may appear at two processing levels (for a review, see MacLeod, 1991). First, the effect may be due to conflict at the level of cognitive or perceptual representations (Hock & Egeth, 1970). This theory assumes that decreased performance in the incongruent condition is due to resolving the conflict

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between the representations of the task-relevant and the task-irrelevant stimulus dimensions. Second, the conflict may arise as a consequence of motor response competition (Posner & Snyder, 1975; Morton & Chambers, 1973). This theory assumes that both the task-relevant and the task-irrelevant features contribute to motor preparation and they compete for dominating the motor output. This response competition results in worsened performance in the incongruent condition. Naturally, the above theories are not mutually exclusive; most probably, both cognitive/perceptual and motor conflict affect performance in Stroop tasks (Szűcs & Soltész, 2007, 2008).

Developmental studies of Stroop tasks have used a number of different experimental paradigms, for example, the classical color–word Stroop task (Comalli, Wapner, & Werner, 1962), the color–object task (Prevor & Diamond, 2005), and the day–night task (Gerstadt, Hong, & Diamond, 1994). A general finding is that the performance difference between the congruent and the incongruent conditions (Stroop interference) decreases with increasing age; that is, older children can resolve the conflict between the task-relevant and the task-irrelevant dimensions more effectively than younger children. Typically, children younger than 5 years cannot cope effectively even with child-friendly Stroop tasks (Gerstadt et al., 1994). Importantly, behavioral developmental Stroop studies did not separate perceptual/cognitive and motor response conflict clearly either by experimental manipulation or by measures specific to cognitive or response conflict. Most investigators consider the ability to overcome Stroop interference to be driven by the development of inhibitory control. In particular, some hypothesized that the superior performance of older children may be due to improved behavioral inhibition abilities, which allow them to override prepotent but task-irrelevant behavioral responses more effectively than younger children (Prevor & Diamond, 2005; Gerstadt et al., 1994). This assumption fits with the motor response competition theory of the Stroop effect, with our previous ERP study (Szűcs, Soltész, Jármi, & Csépe, 2007; see details later), and with the findings of developmental fMRI studies.

A wealth of recent fMRI studies have confirmed a link between prefrontal function and inhibitory control (for a review, see Durston & Casey, 2006). In addition, developmental fMRI studies have found that the activity of the slowly maturing PFC is markedly different in children than in adults. For example, Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002) found that although the most prominent area of activation during inhibitory control tasks in adults was the right ventrolateral PFC, children failed to recruit this area. Similarly, Durston et al. (2002) confirmed that frontal cortex activation is correlated with increasing age and improved performance in a go/no-go task. Importantly, developmental fMRI studies of the Stroop effect reported similar results. For example, in the color–word Stroop task, Adleman et al. (2002) found that whereas parietal lobe activation reaches adult levels by adolescence, PFC activation is still increasing throughout adolescence. Similar findings were reported by a functional near-infrared spectroscopy study in a color–word Stroop task (Schroeter, Zysset, Wahl, & Cramon, 2004). Investigators interpreted their findings as indicating that adult-level performance on Stroop tasks requires PFC resources that are not yet fully developed in children or in adolescents. A likely candidate for this critical resource is behavioral inhibition, underlying the ability to resolve motor response competition.

Although the above fMRI studies could pinpoint the PFC as a brain area whose development is of prime importance in performance in Stroop tasks, the poor temporal resolution of fMRI does not allow for the adequate characterization of motor response competition. Fortunately, in contrast to fMRI, ERPs are able to track electrical brain activity with a practically real-time, millisecond temporal resolution. One especially useful ERP measure for studying motor processes in real time is the lateralized readiness potential (LRP). The computation of the LRP relies on the fact that ERPs recorded at electrodes placed over the motor cortex of the hemisphere contralateral to the response hand are more negative than ERPs over the hemisphere ipsilateral to the response hand. The LRP summarizes these electrical potential differences in a single measure. The LRP is considered to be a real-time measure of motor cortex activation related to response hand preparation/activation (De Jong, Wierda, Mulder, & Mulder, 1988; Gratton et al., 1988). According to its traditional computation, a negative deflection in LRP suggests correct response hand activation, whereas a positive deflection in LRP suggests incorrect response hand activation. The LRP has frequently been used for studying motor processes in adults. However, contrary to its great potential, we know of only two previous studies exploiting the LRP in children (Szűcs et al., 2007; Ridderinkhof & van der Molen, 1995).

Ridderinkhof and van der Molen (1995) used the LRP to detect and to compare the speed of response initiation in 5- to 12-year-old children and adults in an Eriksen flanker task (Eriksen & Eriksen, 1974). In the Eriksen flanker task, participants have to react to a central target stimulus surrounded (flanked) by distractor stimuli. The target stimulus and the distractor stimuli may induce identical (congruent condition) or opposing (incongruent condition) behavioral responses. Similarly to Stroop tasks, performance is worse in the incongruent than in the congruent condition of flanker tasks. Ridderinkhof and van der Molen (1995) used two ERP measures, the peak latency of the P3 ERP wave and the LRP. The P3 wave is considered to index the termination of higher level stimulus evaluation and categorization processes (Donchin, 1981). Accordingly, in Stroop tasks, the peak latency of the P3 wave has been used to study to what extent congruency effects are related to stimulus processing (Szűcs et al., 2007; Ilan & Polich, 1999; Ridderinkhof & van der Molen, 1995; Duncan-Johnson & Koppel, 1981). Further, Ridderinkhof and van der Molen (1995) determined the speed of response activation by monitoring the onset of LRP deviations associated with correct response activation.

Comparing effects on the P3 latency and the LRP allowed for the dissociation of congruency effects related to perceptual/cognitive and motor conflict.

Ridderinkhof and van der Molen (1995) found that RT decreased with increasing age. Further, the latency of the P3 differed to a similar extent between the congruent and the incongruent conditions in all age groups. This suggests that all age groups managed to cope with perceptual/cognitive conflict in a similar manner. In contrast to this, correct response activation measured by the LRP became faster with increasing age. This suggested that older children and adults could control their motor processes more efficiently than younger children. It was concluded that the development of resisting interference between task-relevant and task-irrelevant stimuli was primarily affected by the development of motor response inhibition and the ability to resolve response competition.

Besides detecting the speed of motor cortex activation, the LRP can also be used for the direct monitoring of correct and incorrect response activation. Hence, the LRP is an excellent tool for studying motor response competition itself (De Jong et al., 1988; Gratton et al., 1988). Indeed, previous studies of the Eriksen flanker task in adults have demonstrated incorrect motor cortex activation in correctly responded incongruent trials (Smid et al., 1990; Gratton et al., 1988). This observation suggests that both the target and the distractor stimuli undergo parallel processing and prepare motor processes in parallel. In the incongruent condition, this can result in latent incorrect motor cortex activation even in the absence of overt incorrect response activity. The appearance of incorrect motor cortex activation is interpreted as a neural marker of response competition.

In the developmental study of Ridderinkhof and van der Molen (1995), the time course of incorrect response activation in the incongruent condition relative to the congruent condition was not analyzed in detail. A reason for this might have been that the LRP was rather atypical in that negative LRP deviations (correct response activation) were preceded by positive LRP deviations (incorrect response activation) not only in the incongruent but also in the neutral and congruent conditions. These findings are hard to interpret as in principle no incorrect response activation is predicted in the congruent and neutral conditions. Furthermore, correct response hand activation was followed by incorrect response activation in all conditions, which was again unexpected. One reason for the extraordinary LRP pattern in the study of Ridderinkhof and van der Molen (1995) might have been that an unusually long (1000 msec) baseline was used for the LRP computation.

In our own previous developmental LRP study, we used a shorter, more traditional 100-msec baseline for LRP computation and were able to provide evidence for selective incorrect response activation in the incongruent condition of a Stroop-like task in children (Szűcs et al., 2007). We used the so-called numerical Stroop paradigm in which 9- and 11-year-old children and adults saw two simultaneously presented Arabic digits on a computer screen. Participants decided which number was larger either in numerical magnitude or in physical size. In some cases, the numerical and physical relationship of the stimuli was congruent (e.g., 2 **3**). In other cases, the numerical and the physical relationship of the stimuli was incongruent (e.g., **2** 3). Behavioral measures showed similar congruency effects in both children and adults. However, the LRP showed strong incorrect response hand activation in children in the incongruent condition of the numerical discrimination task. Adults did not demonstrate such effect. Therefore, we concluded that inefficient motor response organization, hence overcoming motor response competition, was a more significant factor in the overall performance of the children than that of the adults. Our data were in agreement with the study of Ridderinkhof and van der Molen (1995). Importantly, both studies suggested that psychophysiological measures are able to pinpoint differences in the cognitive processing of children and adults even if these are not reflected in behavioral performance (Temple & Posner, 1998).

A drawback of the numerical Stroop paradigm used in our previous study was that evaluating numerical magnitude may have been a less familiar task for children than for adults (Szűcs et al., 2007). This may have amplified the difference in motor processing between adults and children. To avoid this problem, here we have used a task, modeled on the numerical Stroop task, in which children are probably as experienced as adults in judging both stimulus dimensions (Figure 1). We asked young children and adults to select from two animals, presented simultaneously on the computer screen, which was larger in

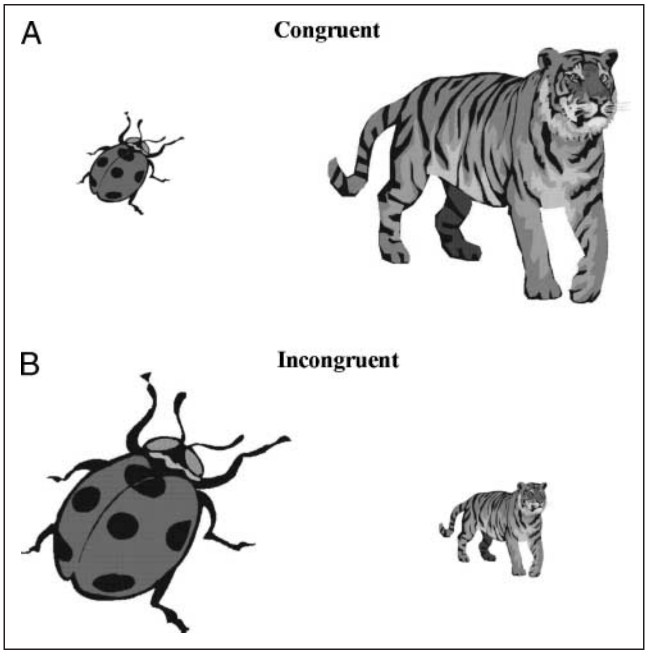

Figure 1. Example stimuli from the experiment. (A) Congruent condition. (B) Incongruent condition.

real life. In the incongruent condition, the animal (e.g., a tiger) that was larger in real life was smaller in actual physical size on the screen than the other animal that was smaller in real life (e.g., a ladybird). In the congruent condition, the animal that was larger in real life was larger in physical size on the screen.

On the basis of our previous study, we expected that incorrect motor cortex activation (reflecting incorrect response hand activation) would appear when the real-life size and the actual physical size of animals were incongruent. Our primary question was whether incorrect response hand activation plays a similar role in both children and adults. Specifically, in line with the findings of Ridderinkhof and van der Molen (1995) and with our previous findings (Szűcs et al., 2007), we hypothesized that incorrect motor cortex activation in the incongruent condition will be stronger in children than in adults. Second, to our knowledge, only the two above studies reported the LRP in children, and only one of them demonstrated a reliable difference in incorrect response hand activation between the congruent and the incongruent conditions (Szűcs et al., 2007). Therefore, here we intended to further confirm the usability of the LRP for tracking correct and incorrect motor cortex activation in children.

Although our main interest was the examination of motor processes using the LRP, we also analyzed the latency and the amplitude of ERP waves thought to be tightly related to stimulus-processing speed. Similarly to Ridderinkhof and van der Molen (1995) and several previous Stroop ERP studies (Szűcs et al., 2007; Ilan & Polich, 1999; Duncan-Johnson & Koppel, 1981), we used the peak amplitude of the P3 wave to index the termination of complex stimulus evaluation and categorization processes (Donchin, 1981). In addition, here we have also analyzed the peak latency of early parieto-occipital visual ERPs thought to be closely related to the earliest phases of perceptual processing (P1, N2, and P2). If congruency effects in the animal-size Stroop task are related to perceptual/cognitive processing, they should affect the peak latency of our ERP peak latency measures. Most importantly, the comparison of effects on ERP peak latency measures and effects on the LRP would allow us to separate the influence of perceptual/cognitive processing and motor response organization on task performance.

In this study, our primary objective was to compare the motor response competition profile of adults and young children. Previous studies have shown that children can effectively cope with Stroop tasks after about 5 years (Gerstadt et al., 1994). Hence, children younger than 5 years old would not respond correctly to enough trials, and there would be insufficient signal strength for ERP analysis. In addition, in our previous ERP study, we have demonstrated considerable motor response competition in somewhat older than 9-year-old children in a numerical Stroop task (Szűcs et al., 2007). Considering the above, in the current study, we focused on the age group that was younger than in our previous study but who could already cope efficiently with Stroop tasks. Therefore, we tested children during the first 3 years of school, approximately between 5.5 and 8.5 years.

METHODS

Originally, 27 children and 17 adults participated in the experiment. Before running any analyses, the data for 13 children and 3 adults were rejected because of EEG artifacts. This left 14 children (7 girls) and 14 adults (6 women) in the sample. The mean age of children was 7 years 6 months (range = 5 years 10 months to 8 years 8 months). The mean age of adults was 30 years 6 months (range = 22 years 0 month to 59 years 2 months). Eleven children were right-handed. Eleven adults were right-handed. Adults were graduate and undergraduate students and staff at the University of Cambridge. Children received a T-shirt as a token of gratitude for participation. Adults received payment.

Stimuli were colored pictures of two animals. Example stimuli are shown in Figure 1. Stimuli were selected after piloting a selection of animal pictures with 40 children of the same age as the main study. Fifty animal pictures were shown to children, and they were asked to describe them as small-, medium-, or large-sized animals. Only those that all children agreed were either small or large were used in the study (31 in total, 14 small and 17 large). This ensured that there was no uncertainty about an animal being large or small in real life. In addition, a game was played with the children before the experiment to ensure that they understood what was required in the task—to select the animal that was larger in real life. This game involved helping a zoo keeper sort his animals according to size so he could put them into appropriately sized cages and involved pictures where animals were the same size and different sizes. The children all seemed confident that they understood the task requirements.

During the experiment, stimuli were presented in the middle of a 17-in. computer screen. One animal was presented to the left, the other to the right of the center. Subjects were instructed to press a button on the side corresponding to the animal that was bigger in real life. In the congruent condition, the animal that was larger in real life was presented in a larger picture than the animal that was smaller in real life. In the incongruent condition, the animal that was larger in real life was presented in a smaller picture than the animal that was smaller in real life. Subjects gave behavioral responses by pressing a button on a game pad with the left or right index finger. Half of the congruent/incongruent trials required a left/right hand response. Stimulus series were carefully constructed so that consecutive stimuli could not induce response/processing bias. This was achieved by assuring that congruent and incongruent epochs requiring either a left-hand or a right-hand response were preceded by epochs belonging to each response hand and congruency condition an equal number of times.

Each trial consisted of a fixation sign (drawing of an eye) shown for 500 msec followed by a 1000-msec blank period, and the stimulus was presented for a maximum of 3000 msec. The stimulus disappeared when the subject gave a response. The offset of the stimulus was followed by a 1000-msec blank period. Participants were advised to blink only when they saw the drawing of an eye. There were six blocks of 48 stimuli (altogether 144 congruent and 144 incongruent stimuli). The experiment was preceded by 16 practice stimuli (half congruent). Children and adults committed 0–2 errors during the practice block. Stimuli were presented by the presentation program of the Neurobehavioral Systems. Data were recorded in an acoustically and electrically shielded testing booth. Only correctly responded trials were included in both the behavioral and the EEG analysis.

Accuracy and RT were analyzed by a 2 × 2 × 2 mixed design ANOVA. Group (children vs. adults) was a between-subjects factor. Within-subject factors were Congruency (congruent vs. incongruent) and Response Hand (left vs. right). Post hoc Tukey tests were used to examine ANOVA contrasts.

EEG was recorded by an Electrical Geodesics system with a 65-channel Geodesic Sensor Net. Electrode locations are shown in Figure 2. The sampling rate was 500 Hz. An on-line band-pass filter of 0.01–70 Hz was used. The data were band-pass filtered between 0.01 and 30 Hz off-line and were recomputed to average reference. Epochs extended from −100 to 1000 msec relative to stimulus presentation. Data were baseline corrected by a baseline (−100 to 0 msec relative to stimulus presentation). Epochs containing ocular artifacts (monitored at electrodes below, above, and next to the eyes) and epochs containing voltage deviations exceeding ±100 μV relative to baseline at any of the recording electrodes were rejected. Participants with less than 60% of all trials accepted after artifact rejection were excluded from the sample.

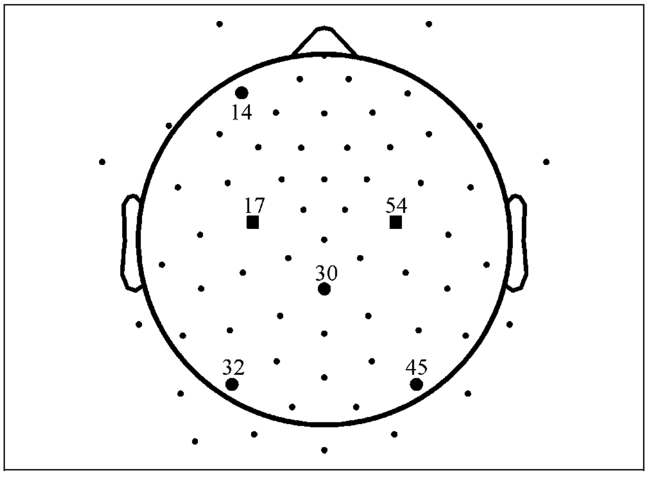

Figure 2. The electrode net used in the experiment. Electrodes used for lateralized readiness potential (LRP) computation are marked by squares (electrodes 17 and 54). Electrodes shown in other figures are marked by large dots.

The LRP was computed as proposed by Coles (1989):

$$[(\mathrm{ER}-\mathrm{EL})_{\text{left hand response}} + (\mathrm{EL}-\mathrm{ER})_{\text{right hand response}}]/2,$$

where ER denotes the amplitude of the ERP at an electrode placed over the right motor cortex, and EL denotes the amplitude of the ERP at an electrode placed over the left motor cortex. Traditionally, the LRP is computed using electrodes C3 and C4 placed according to the international 10–20 electrode system. Here we used the EGI Geodesic Sensor Net where electrodes do not fit the 10–20 system. We chose electrode 54 as the electrode above the right motor cortex and electrode 17 as the electrode above the left motor cortex. These electrodes were chosen because they are as close to the original C3/C4 locations as possible. With this electrode placement, we detected the LRP with exactly the expected morphology and timing in our previous LRP study (Szűcs & Soltész, 2008).

According to convention, a negative LRP indicates a correct response tendency, and a positive LRP indicates an incorrect response tendency. The first step of LRP analysis examined whether the LRP significantly deviated from baseline at all. This must be established to ascertain the presence of correct or incorrect response activation. The deviation of the LRP from baseline was tested by point-by-point two-tailed one-sample t tests against zero ($p < .05$). In a second step, point-by-point mixed design Group × Congruency ANOVAs were run on LRP curves. Our main interest was comparing congruency effects within and across groups. Hence, in a third step, pairwise planned comparisons were carried out between the congruent and the incongruent condition separately in adults and children; and also between adults and children separately for the congruent and the incongruent conditions. The amplitude of the LRP was compared between the congruent versus the incongruent conditions (separately for adults and children) by point-by-point two-tailed matched t tests ($p < .05$). The LRP of children and adults (separately for the congruent and the incongruent conditions) was compared by point-by-point two-tailed independent-sample t tests ($p < .05$). The above results were confirmed by overall t tests run on the mean amplitude of the intervals found to be significant by point-by-point t tests.

The peak latency of the parieto-occipital P1, N2, and P2 ERP waves was determined as the peak latency of the most positive (P1 and P2) or negative (N2) amplitude peak at electrodes 32 and 45. Peak latencies were measured in the following intervals: P1, 90–170 msec; N2, 140–260 msec; and P2, 210–400 msec. Wide latency windows were used so that the data for both children and adults could be measured reliably. Peak latencies were tested by a Group × Congruency × Electrode (electrodes 32 and 45) mixed design ANOVA. The peak latency of the P3 wave was determined on electrode 30, and P3 data were analyzed by a Group × Congruency ANOVA. The P3 wave was identified as the most positive peak between 400 and 800 msec.

In a further analysis, we examined congruency effects in the amplitude of ERPs recorded at all 65 channels at all sampling points. ERPs were analyzed by point-by-point Congruency × Response Hand ANOVAs in each age group. To protect against Type 1 errors, significant congruency effects were considered to appear where the effect of congruency was significant at $p < .025$ in at least four electrode channels during 15 consecutive sampling points. Effects were confirmed by running further Congruency × Electrode ANOVAs on the mean amplitude of the intervals showing congruency effects according to point-by-point ANOVAs. Congruency × Electrode ANOVAs were run separately for electrodes showing mean negative and mean positive voltage in incongruent–congruent difference potentials. This was done to avoid the main effect of congruency being canceled out as a result of averaging electrodes with positive and negative voltages. Significant congruency effects were visually illustrated by spline-interpolated voltage distribution topographic scalp maps of incongruent minus congruent difference potentials.

Analyses were completed in Matlab 6.0 and Statistica 6.0. Scalp maps were produced using the EEGLab Matlab package (Delorme & Makeig, 2004).

RESULTS

Behavioral Data

Accuracy and RT are given in Table 1. Children and adults solved the task at the same level of accuracy (95% vs. 97%, $p = .15$). There were more correct responses in the congruent than in the incongruent condition, $F(1, 26) = 10.47$, $p = .0032$. There were more correct responses with the right hand than with the left hand, $F(1, 26) = 6.80$, $p = .0148$. The congruency effect was stronger with the left hand than with the right hand, Congruency × Hand, $F(1, 26) = 7.21$, $p = .0124$. According to Congruency × Hand contrasts, the congruency effect was significant in both the left hand and the right hand (Tukey tests for both, $p < .0005$).

The analysis of RT revealed that adults reacted 293 msec faster than children, $F(1, 26) = 67.81$, $p < .0001$. Congruent trials were responded to 89 msec faster than incongruent trials, $F(1, 26) = 175.70$, $p < .0001$. The effect size of congruency was larger in children (120 msec) than in adults (57 msec), Congruency × Group interaction, $F(1, 26) = 22.26$, $p < .0001$. According to Congruency × Group contrasts, the congruency effect was significant at the same level in both children and adults (Tukey tests for both, $p < .0002$).

Table 1. Reaction Time and Accuracy in Children and Adults

	Reaction Time (msec)		*Accuracy (%)*	
	Congruent	*Incongruent*	*Congruent*	*Incongruent*
Children	825 ± 38	945 ± 38	96 ± 2	95 ± 2
Adults	564 ± 38	621 ± 38	99 ± 2	97 ± 2

Values are presented as mean ± standard error.

ERP Data

The range of the proportion of accepted trials was 64–92% in children and 78–98% in adults. LRPs are shown in Figure 3. The intervals where the LRP significantly deviated from the baseline are marked by rhombi in Figure 3. In the congruent condition, the LRP deviated negatively (correct response activation) in both adults and children. In adults, significant deviation happened between 320 and 470 msec (average voltage during this interval = -1.29 μV), $t(14) = -2.74$, $p = .0167$. In children, significant negative deviation onset 50 msec later than in adults and lasted between 370 and 496 msec (-2.93 μV), $t(14) = -2.31$, $p = .0379$. In the congruent condition, the amplitude of the LRP was more negative in children than in adults between 130 and 200 msec, $t(26) = -2.13$, $p = .042$, and between 410 and 530 msec, $t(26) = -2.29$, $p = .03$ (see horizontal markers in Figure 3).

In the incongruent condition, initially both children and adults demonstrated a positive LRP deflection, that is, incorrect response activation. In adults, this incorrect response activation was significant for a duration of 74 msec between 206 and 280 msec (+0.83 μV), $t(14) = 3.63$, $p = .003$. In children, the incorrect response activation was significant for a duration of 114 msec, between 220 and 334 msec ($t = +2.58$ μV), $t(14) = 3.18$, $p = .0072$. The amplitude of the LRP had positive polarity in children during the entire interval between 106 and 460 msec. During this time, the amplitude of the LRP was more positive in children than in adults between 106 and 200 msec, $t(26) = 3.14$, $p = .004$, and between 226 and 460 msec, $t(26) = -4.57$, $p = .003$. The above results suggest that initially incorrect response activation appeared in the incongruent condition in both adults and children. Further, this incorrect response activation was stronger in children than in adults. In accordance with the above pairwise differences between children and adults, point-by-point Group × Congruency ANOVAs run on LRPs found Group × Congruency interactions ($p < .05$) between 112 and 194 msec and between 324–460 and 462–508 msec.

The incorrect response activation was followed by correct response activation in both adults and children. In adults, the LRP showed correct response activation between 344 and 828 msec (-3.42 μV), $t(14) = -4.81$, $p = .0003$. In children, the LRP showed correct response activation between 532 and 714 msec ($t = -2.96$ μV), $t(14) = -2.9$, $p = .0123$. The amplitude of the LRP was more positive in children than in adults between 460 and 582 msec, $t(26) = 3.09$, $p = .005$.

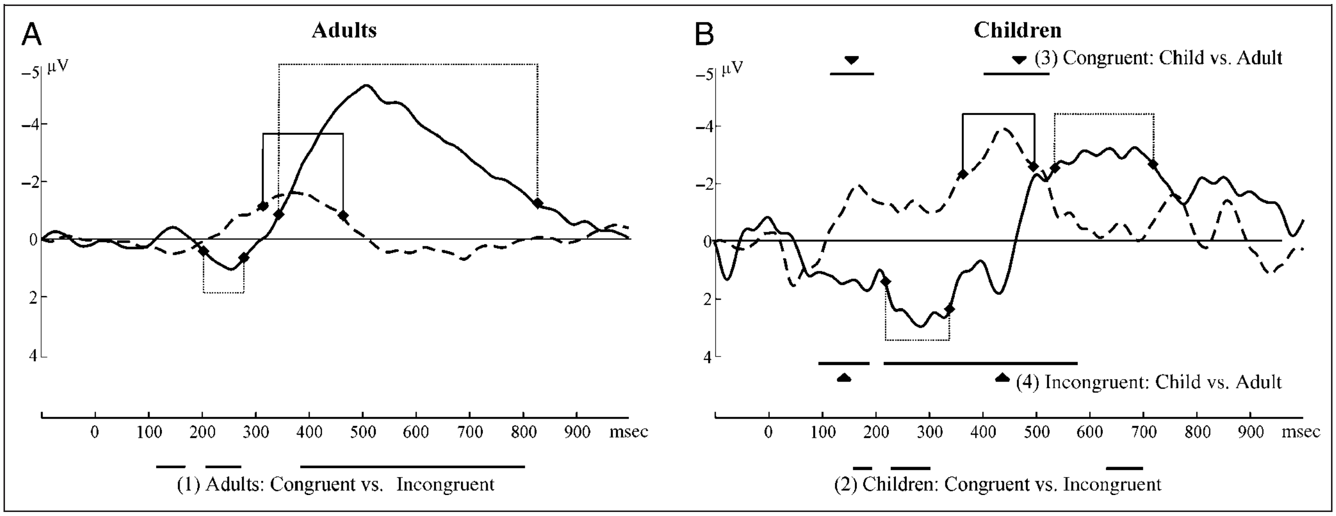

Figure 3. The lateralized readiness potential (LRP) in (A) adults and (B) children. Dotted lines depict the LRP in the congruent condition; continuous lines depict the LRP in the incongruent condition. The rhombi connected by lines denote the intervals where the LRP significantly deviated from baseline. The results of point-by-point *t* tests are depicted by horizontal lines. Numbered lines refer to the following *t* tests: (1) comparing the congruent and incongruent condition in adults; (2) comparing the congruent and incongruent condition in children; (3) comparing adults and children in the congruent condition; and (4) comparing adults and children in the incongruent condition. Further statistical results are detailed in the text.

The above differences between the congruent and the incongruent conditions were further confirmed by directly comparing the amplitude of the LRP in the congruent and the incongruent conditions (see horizontal markers in Figure 3). In children, the amplitude of the LRP differed between the congruent and the incongruent conditions between 160 and 200 msec, $t(14) = -2.55, p = .023$, between 230 and 304 msec, $t(14) = -2.64, p = .02$, and between 632 and 700 msec, $t(14) = 2.45, p = .028$. In adults, the amplitude of the LRP differed between the congruent and the incongruent conditions between 118 and 172 msec, $t(14) = 3.74$, $p = .002$, between 210 and 276 msec, $t(14) = -2.80$, $p = .014$, and between 386 and 804 msec, $t(14) = 4.12, p = .001$.

The speed of stimulus evaluation and categorization processes was determined by examining the peak latency of the P3 wave. In addition, the peak latency of early visual ERP waves was also examined (parieto-occipital P1, N2, and P2). ERPs are shown in Figure 4. The peak latency of waves is shown in Figure 5. The P1 peaked 28 msec earlier in adults than in children (118 vs. 146 msec), $F(1, 26) = 60.34$, $p < .0001$. The N2 peaked 46 msec earlier in adults than in children (168 vs. 214 msec), $F(1, 26) = 73.86, p < .0001$. The P2 peaked 94 msec earlier in adults

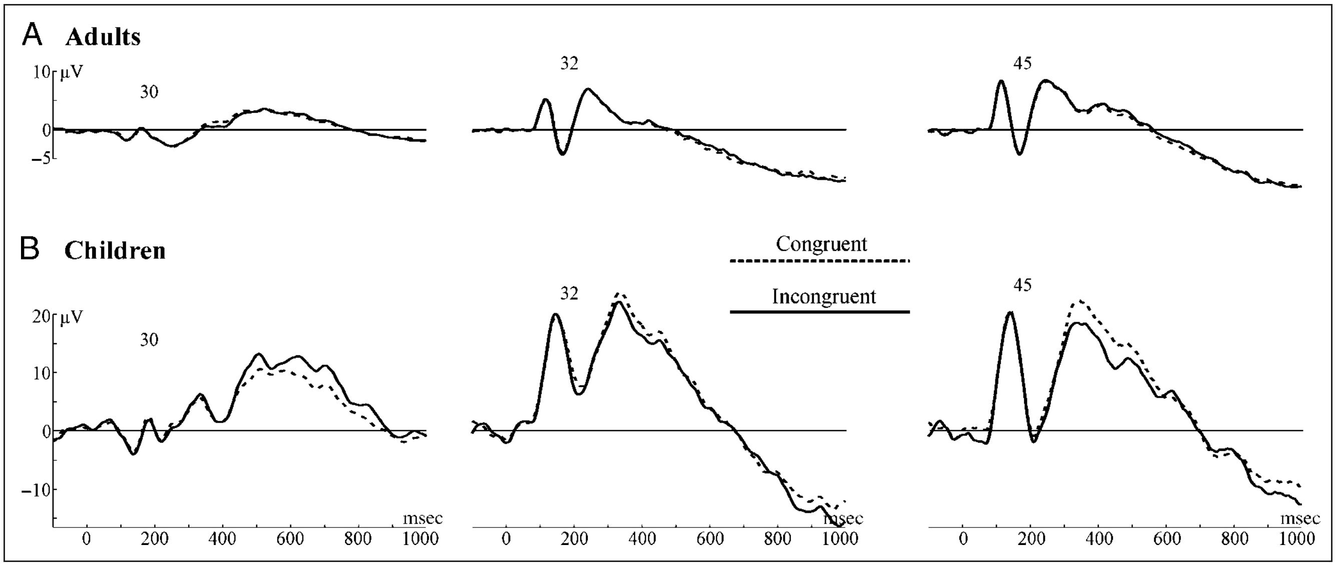

Figure 4. ERPs in (A) adults and in (B) children at electrodes 30, 32, and 45. See Figure 2 for electrode positions.

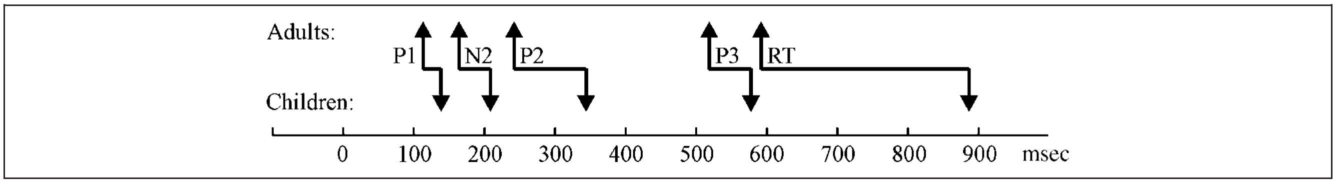

Figure 5. The latency of ERP waves P1, N2, P2, and P3 and the RT in adults and children. The time scale is the same as for ERPs; that is, it is given relative to stimulus presentation (zero time).

than in children (248 vs. 342 msec), $F(1, 26) = 270.37$, $p < .0001$. The P3 wave peaked 61 msec earlier in adults than in children (521 vs. 582 msec), $F(1, 26) = 8.33$, $p < .0077$. There were no congruency effects in the latency of any of the ERP waves.

To check consistency with our previous results (Szűcs & Soltész, 2007, 2008), point-by-point ANOVAs were run on the amplitude of ERPs at all sampling points. These ANOVAs revealed congruency effects between 310 and 360 msec in adults and between 280 and 420 msec in children. The topography of effects (incongruent minus congruent difference potentials) is shown in Figure 6. In adults, the effect appeared over six central electrodes, ANOVA result for overall congruency effect, $F(1, 13) = 7.25$, $p < .0184$. There were no Congruency × Electrode interactions. In children, the effect appeared at five left frontal, ANOVA result for overall congruency effect with positive amplitude, $F(1, 13) = 15.92$, $p < .0015$, and 12 posterior electrodes, ANOVA result for overall congruency effect with negative amplitude, $F(1, 13) = 13.11$, $p < .0031$. There were no Congruency × Electrode interactions.

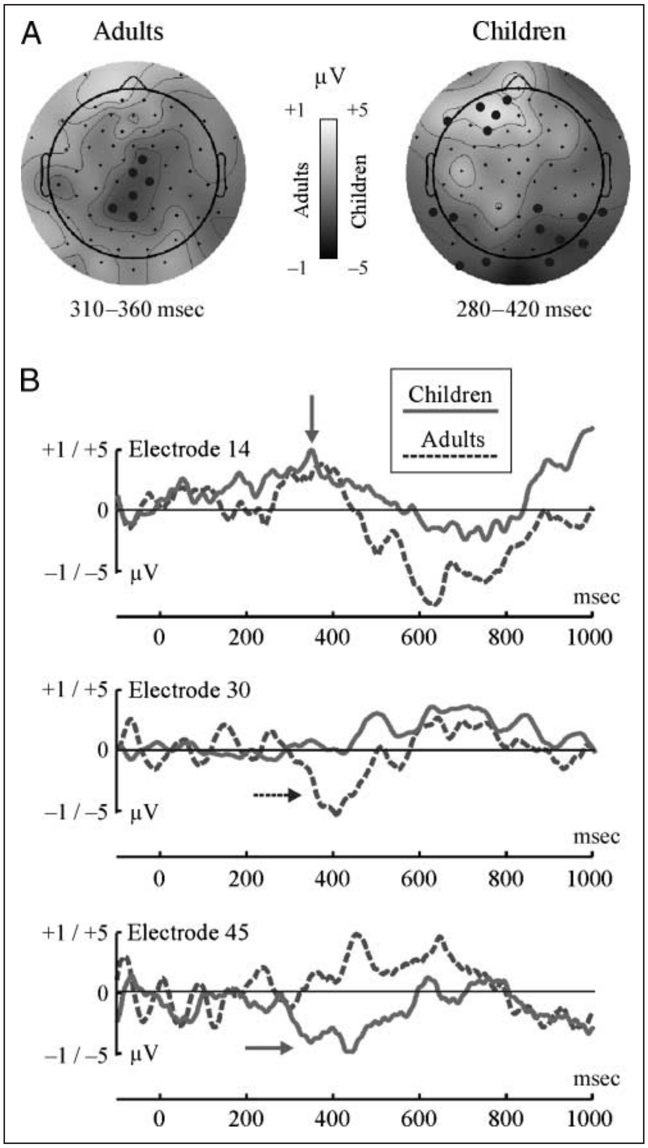

Figure 6. (A) Spline-interpolated scalp maps of incongruent minus congruent difference potentials. Maps show the distribution of mean voltage in the designated time intervals. Electrodes demonstrating significant congruency effects are marked by large dots ($p < .025$). The scale is ±1 μV for adults and ±5 μV for children. (The scale is different for adults and children because ERPs had larger amplitudes in children than in adults. However, the proportions of scales are comparable across groups.) (B) Incongruent minus congruent difference potentials at representative electrode locations (for locations, see Figure 2). The microvolt scale is ±1 μV for adults and ±5 μV for children. Significant effects are marked by arrows (continuous arrow: children; dashed arrow: adults).

DISCUSSION

We compared correct and incorrect motor response activation in children and adults in an animal-size Stroop task. The LRP was used as a direct real-time measure of motor response activation. The peak latencies of ERP waves were used as measures of the speed of stimulus evaluation and categorization. We found that children solved the task slower than adults. Both groups showed robust congruency effects in RT and in LRP but not in the latency of ERP waves. According to our expectation, the incorrect response activation measured by the LRP was stronger in children than in adults. Measures of stimulus processing speed could not account for the RT difference between children and adults, for the congruency effects in any groups, or for the larger congruency effect in children than in adults. In contrast, the incorrect response activation demonstrated in the LRP data explains both congruency effects and overall RT differences between children and adults.

In general, children solved the task 293 msec slower than adults. However, the ERP peak latencies of children and adults, usually considered to correlate strongly with stimulus processing speed, differed only by 28–94 msec. This suggests that stimulus processing speed alone cannot explain at least 200 msec speed difference between children and adults. The LRP data also suggest that stimulus processing speed was similar in the two groups. According to our expectations, the onset of the LRP was delayed in children relative to adults. However, this delay was very slight relative to the RT difference. Correct response activation onset 50 msec later in children than in adults according to the LRP. Similarly, in the incongruent condition, incorrect response activation happened only 14 msec later in children than in adults. The very slight delay of LRP onset in children relative to adults suggests that stimuli elicited motor activation with very similar speed in both conditions in both children and adults. This implies that the speed of stimulus processing is very similar in children and in adults. The LRP and the ERP peak data both indicate that the slight delay in stimulus processing in children cannot explain the 293-msec RT difference in children relative to adults.

Besides the RT difference between children and adults, another robust RT effect was that congruent trials were responded to faster than incongruent trials. Again, the latency of ERP waves could not explain these congruency effects. In fact, there were no congruency effects on the latency of ERP waves at all. In contrast, there were robust congruency effects on the LRP: Although in the congruent condition there was only correct response activation, initially there was robust incorrect response activation in the incongruent condition in both children and adults. The incorrect response activation can be explained by assuming that both the task-relevant and the task-irrelevant dimensions of the stimuli were processed in parallel and both parallel-processed dimensions activated motor responses (Eriksen & Schultz, 1979; Posner & Snyder, 1975). In the incongruent condition, the task-irrelevant physical size of the animal prompted a response with the incorrect hand. Hence, incorrect response (motor cortex) activation appeared in the LRP. This incorrect response activation must have been inhibited to give a correct behavioral response. Error rates did not differ between children and adults. This suggests that both children and adults successfully inhibited the incorrect response tendency and ultimately gave a correct behavioral response. The appearance of incorrect response activation is in line with our expectations, and it is a reasonable explanation for the RT difference between the congruent and incongruent conditions.

The insensitivity of ERP peak latencies to Stroop-type congruency effects is in line with some previous studies of the classical color–word Stroop effect (Ilan & Polich, 1999; Duncan-Johnson & Koppel, 1981). These studies used the latency of the P3 ERP wave as a measure of the completion of stimulus analysis (for more refined views on the P3, see Dien, Spencer, & Donchin, 2004) and could not demonstrate congruency effects in the latency of ERP waves. Similarly, Szűcs et al. (2007) did not find congruency effects on the latency of the P3 in 9- and 11-year-old children in a numerical Stroop task. It is important to note that, naturally, not detecting incongruency effects in the peak latency of ERP waves used as measures of stimulus processing speed can be considered a null effect. Hence, the lack of congruency effects in stimulus processing as measured by ERPs does not exclude the possibility that such effects exist. However, it is clear that although ERPs did not demonstrate congruency effects related to stimulus processing, the robust motor response activation effects shown by the LRP can serve as an explanation for congruency effects.

Besides the fact that the congruency effect was robustly significant in RT in both children and adults, there was a significant Congruency × Group interaction in RT as well. This interaction appeared because the effect size of congruency was larger in children than in adults (120 vs. 57 msec). In line with this difference, the amplitude of the LRP reflecting incorrect response activation was also larger in children than in adults. Further, it was also found that the duration of significant incorrect response activation demonstrated by the LRP was about 40 msec longer in children than in adults. In fact, the duration of significant incorrect response activation as expressed by the LRP (114 msec in children and 74 msec in adults) was in very good agreement with the size of the behavioral RT congruency effect in both children and adults. Further, in adults, it took 54 msec to activate the correct response in the incongruent condition after the offset of incorrect response activation (280 vs. 334 msec), whereas in children it took 192 msec (340 vs. 532 msec). In contrast to the LRP results, there was no correlate of differential incongruency effects in the latency of ERP waves.

In contrast to the lack of congruency effect in the latency of ERP waves, there were congruency effects in both children and adults in the amplitude of ERPs. The timing of congruency effects was in good agreement with our previous studies using a numerical Stroop paradigm requiring magnitude decisions (Szűcs & Soltész, 2007, 2008) and with other studies of the Stroop effect (for a review, see Szűcs & Soltész, 2007). In adults, the central topography of the effect was very similar to interference effects found between 330 and 460 msec in our previous studies and to congruency effects found by other ERP Stroop studies (Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 1999). Liotti et al. (2000) interpreted this topography as a possible sign of the conflict monitoring and response selection activity of the ACC, whereas others hypothesized that it may be related to the N400 ERP wave thought to be a marker of semantic/contextual mismatch (for a detailed discussion, see Szűcs & Soltész, 2007).

The topography of congruency effects was very dissimilar in children and adults. However, because ERPs lack anatomical specificity, topographic findings cannot be interpreted unequivocally. One possibility is that the differential topography signals the involvement of different neural networks in children and adults. However, it is also possible that the relative strengths of the same neural generators were different in the two groups, or that topographic differences can be attributed to differential anatomical parameters in groups (e.g., size and orientation of gyri and sulci, skull thickness). Importantly, the period with ERP amplitude congruency effects (50 msec in adults and 120 msec in children) was again in good agreement with the effect size of congruency effects in RT. Further, ERP amplitude effects appeared well before the peak of the P3 and approximately coincided with the maximal amplitude of incorrect response activation measured by LRP in both groups. Hence, we speculate that the topography of congruency effects may be related to the conflict detection activity of ACC as hypothesized by Liotti et al. (2000). Combined ERP/fMRI studies may help to settle this anatomical hypothesis.

Overall, our LRP results suggest that incorrect response activation was stronger and lasted longer in children than in adults. In theory, there may be at least two explanations for why larger and longer lasting incorrect response activation was initiated in children than in adults. First, it is possible that the less developed inhibitory processes of children (Prevor & Diamond, 2005; Deak & Narasimham, 2003; Gerstadt et al., 1994), thought to rely on the maturation of the frontal cortex (Adleman et al., 2002; Bunge et al., 2002; Durston et al., 2002), took more time to overcome incorrect response activation than in adults. Second, it could be assumed that initial incorrect response activation itself was stronger in children than in adults. This could have happened for example because of the less successful attentional selection of the task-relevant stimulus dimension in children. In this case, the larger initial incorrect response activation in children may have been simply strong enough to survive inhibitory processes for a longer period than in adults. Our combined LRP and ERP peak data favor the first explanation. As discussed, ERP stimulus processing speed measures did not show any differences between the congruent and the incongruent conditions. This suggests that the task-relevant stimulus dimension was selected with equal success in both the congruent and the incongruent conditions. Hence, we attribute LRP effects to differential behavioral inhibition abilities between adults and children. This conclusion is in line with previous inferences suggesting that despite similar stimulus processing speeds, children have longer RTs than adults and that these can be attributed to immature motor response organization processes relying on frontal cortex inhibition mechanisms (Szűcs et al., 2007; Temple & Posner, 1998; Ridderinkhof & van der Molen, 1995, 1997).

Overall, our data suggest that strong incorrect motor response activation can effectively explain the larger RT congruency effect in children than in adults. In general, measuring motor processing speed and incorrect motor activation in children may serve as a valuable and necessary developmental marker when characterizing performance. In relation to this, here we have demonstrated that the LRP provides an excellent tool for tracking motor response activation in children in real time. This raises the possibility that the LRP may prove a valuable marker in the study of the development of inhibitory processes. This is potentially important because the significance of inhibition skills in child development has been increasingly recognized in recent years. There is now extensive evidence, for example, of the relationship between inhibition and theory of mind; that is, the emerging ability of children to recognize and to take account of their own mental processes and those of others (Lang & Perner, 2002) and the functional links with metacognitive and self-regulatory skills (i.e., the ability to monitor and control one's own cognitive and affective processes) are also now beginning to be explored (Fernandez-Duque, Baird, & Posner, 2000). Blair and Razza (2007), for example, in a longitudinal study of 3- to 5-year-olds from low-income homes in the United States, have recently demonstrated that early mathematics and reading ability were uniquely predicted by various aspects of self-regulation and executive function, particularly inhibitory control. Similar work is likely to have not only developmental but also considerable educational significance.

Finally, an important methodological point to note is that in our previous study, we found that the polarity of the LRP was opposite in children to that in adults (Szűcs et al., 2007). That is, correct responses were coupled with negative LRP deflections in adults as usual. However, correct responses were coupled with positive LRP deflections in children. In contrast to our previous observation, in the current study, we found that the LRP had a similar polarity in both adults and children. That is, correct responses were accompanied by negative LRP deflections in both groups. A possible explanation of this discrepancy is that the LRP may be highly sensitive to variations of some anatomical parameters of the brain. For example, Brunia and Vingerhoets (1980) found that foot movements are preceded by ERPs that are more positive over the hemisphere contralateral to the moving foot than to the hemisphere ipsilateral to the moving foot. That is, the hemispheric polarization is opposite for hand and foot movements. This distinct polarization can most probably be attributed to the different anatomical locations of neurons in the motor cortex guiding hand and foot movements (Miller & Hackley, 1992). The sensitivity of the LRP to anatomical parameters suggests that disparity in anatomical parameters can explain occasional LRP polarity differences between different groups of children and/or between children and adults. Hence, LRP polarity differences in children between our current and previous studies (Szűcs et al., 2007) can most probably be explained by minute differences between the anatomical parameters of the brains of our current and previous child participants. To be able to better exploit the LRP, it will be important to track its development by behavioral studies.

In summary, taken together with previous findings (Szűcs et al., 2007; Ridderinkhof & van der Molen, 1995), our results establish the LRP as a reliable marker of correct and incorrect motor cortex activation in children. Most importantly, the LRP demonstrated robust incorrect response activation in both children and adults in the incongruent condition of an animal-size Stroop task. At the same time, both adults and children solved the task at the same level of accuracy. The above suggests that the animal-size Stroop paradigm is a well-balanced task for comparing motor response activation and inhibitory control in children and adults. Interpreting our results, we conclude that neither the RT discrepancy between children and adults nor the congruency effects could be explained by differential stimulus processing speed between children and adults. However, when differences in correct and incorrect motor response activation (as detected by the LRP) between children and adults are taken into consideration, congruency effects in general, stronger congruency effects in children than in adults, and the generally slower RT of children than adults can be explained. This allows for the conclusion that improvement in motor response organization is a developmental phenomenon of major importance (Ridderinkhof & van der Molen, 1995, 1997). Hence, motor response activation speed and motor inhibition skills should be considered in cognitive tasks with children in certain situations. How developing motor abilities relate to emerging metacognitive and self-regulatory processes is a further question. We have demonstrated that the LRP provides an excellent tool for studying motor response competition and motor cortex activation in general in children.

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