The Relationship Between Internal Motor Imagery and Motor Inhibition in School-Aged Children: A Cross-Sectional Study

Cuiping Wang[1], Wei Li[1], Yanlin Zhou[1], Feifei Nan[1], Guohua Zhao[2], and Qiong Zhang[1]

[1] Department of Psychology and Behavioral Sciences, Zhejiang University

[2] Department of Neurology, Second Affiliated Hospital, College of Medicine, Zhejiang University

ABSTRACT

Functional equivalence hypothesis and motor-cognitive model both posit that motor imagery performance involves inhibition of overt physical movement and thus engages control processes. As motor inhibition in internal motor imagery has been fairly well studied in adults, the present study aimed to investigate the correlation between internal motor imagery and motor inhibition in children. A total of 73 children (7-year-olds: 23, 9-year-olds: 27, and 11-year-olds: 23) participated the study. Motor inhibition was assessed with a stop-signal task, and motor imagery abilities were measured with a hand laterality judgment task and an alphanumeric rotation task, respectively. Overall, for all age groups, response time in both motor imagery tasks increased with rotation angles. Moreover, all children's response times in both tasks decreased with age, their accuracy increased with age, and their motor inhibition efficiency increased with age. We found a significant difference between 7-year-olds and 9-year-olds in the hand laterality judgment task, suggesting that the involvement of motor inhibition in internal motor imagery might change with age. Our results reveal the underlying processes of internal motor imagery development, and furthermore, provide practical implications for movement rehabilitation of children.

KEYWORDS

internal motor imagery
motor inhibition
school-aged children
cross-sectional

INTRODUCTION

Motor imagery is the ability to retrieve movement information from long-term memory and then manipulate it in working memory without actually performing the movement (Farah, 1984). Motor imagery plays an important role in motor performance, skill training, and motor recovery (Glover et al., 2020; see a review by Guillot et al., 2012).

Motor imagery can be performed using kinesthetic motor imagery (KMI) and/or visual motor imagery (VMI, Guillot et al., 2012). Kinesthetic motor imagery requires an individual to mentally rehearse performing a specific action, involving the perception of muscle contractions and stretching, while VMI requires an individual to imagine watching themselves or another individual performing a given action (e.g., Callow & Waters, 2005; Guillot et al., 2009; Moran et al., 2012). Researchers suggest that VMI and KMI activate similar neural areas in the right supplementary motor area (BA6), but also show distinct activation. In particular, the VMI makes reference to the visual properties of visual perception, activating the dorsal (including occipital, parietal and frontal brain areas), and ventral stream areas (including the supplementary motor cortex and the precentral gyrus), while KMI involves greater motor simulation processes closely related to the form and timing of actual movements, activating subcortical areas, including the basal ganglia and cerebellum (Guillot et al., 2009; Jiang et al., 2015; Michelon et al., 2006). Visual motor imagery is divided into two

Corresponding author: Qiong Zhang, Department of Psychology and Behavioral Sciences, Zhejiang University.

E-mail: zhangqiongzgh@zju.edu.cn

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different and specific imagery modalities: internal and external VMI (Hall, 2001; Robin et al., 2020; Williams et al., 2012). For external VMI, participants have to imagine realizing a specific motor action as spectators of their own action (third-person imagery perspective), which can be likened to watching themself on a television or from another person's perspective. For internal VMI, participants have to mentally simulate performing a motor action through their own eyes (first-person imagery perspective), that is, as if they are viewing a camera that is placed on their foreheads whilst performing the movement (Hall, 2001). Studies report distinctively different brain activities when participants are asked to imagine internal and external perspectives (Jiang, et al., 2015; Seiler et al., 2015). Differentiating internal and external VMI can be essential for achieving optimal motor performance, thus providing beneficial motor imagery interventions (Robin et al., 2020). Notably, KMI is considered to be closer to an internal than an external VMI perspective (Guillot et al., 2009).

The biological and cognitive process underlying motor imagery are explained by many models and hypotheses. The functional equivalence hypothesis proposes that motor imagery and overt actions rely on overlapping brain areas such as the superior parietal, premotor cortex, primary motor cortex, basal ganglia, and cerebellum (e.g., Batula et al., 2017; Eaves et al., 2016; Guillot et al., 2009; Hardwick et al., 2018; Hétu et al., 2013; Hohlefeld et al., 2011; Jeannerod, 1994, 2001; Kim et al., 2017; Munzert et al., 2009; Vry et al., 2012). However, motor imagery involves a motor plan which is prevented from operating on the body. This mechanism allows individuals to evaluate the potential consequences of the future action and provides information for consciously monitoring their mental state, and controlling the overt action. Thus, it engages control processes (Jeannerod, 2001). Another account is the motor-cognitive model, which posits that motor imagery can be divided into two stages of action planning and real-time execution control (e.g., Elliott et al., 2001; Glover, 2004). At the planning stage, motor imagery and overt actions are functionally and neurologically equivalent (Glover & Baran, 2017). However, the execution of motor imagery differs from that of overt actions, specifically, the latter use visual and proprioceptive feedback to handle and adjust ongoing movements, while the former is unable to use these sources of information due to the absence of physical movement. Hence, it is a necessary process to prevent overt movement during the execution of motor imagery (e.g., Cameron et al., 2009). Taken together, both theories note that motor inhibition is involved in cognitive processes of motor imagery (for a review see Guillot et al., 2012).

As for motor inhibition, also referred to as behavioral inhibition, response inhibition, and prepotent response inhibition, it is usually defined as the ability to process a prepotent motor response and withhold the response, which requires attending to task-relevant signals, planning, executing appropriate actions, and stopping actions rapidly even after initiation (Dutra et al., 2018). Recently, researchers have investigated the relation between motor inhibition and motor imagery and provided interesting findings. For instance, Angelini et al. (2015) asked participants to imagine themselves in a first-person perspective when performing a motor imagery task. That is, they were required to perform a KMI and visually imagine the movement as well. A putative inhibitory network was activated during the motor imagery task, which was partially overlapping with those activated when motor inhibition is needed. But research on the functional relation between internal first-person perspective motor imagery and motor inhibition is very limited. Thus, the first goal of the present study was to add to that literature and to explore whether the ability of internal motor imagery correlates with the ability of motor inhibition.

Meanwhile, understanding the developmental trend of motor imagery in children can provide a window into the underlying processes of motor development. Evidence shows that children with congenital motor disorders, such as cerebral palsy and developmental coordination disorder, have problems in both motor imagery and motor control, but empirical studies on motor imagery training in children are scarce (Spruijt et al., 2015). Thus, it is necessary to study children's capacities of both motor imagery and motor inhibition and to provide a rationale for motor imagery training in children with motor impairments. Children's motor imagery ability is subjected to physiological maturation and development (Casey et al., 2005; Spruijt et al., 2015). Concurrently, children's motor imagery ability is also accompanied by cognitive and motor development. For example, executive control significantly improves between 6 and 8 years of age (e.g., Carlson et al., 2004; Ikeda et al., 2014; Moffitt et al., 2011), during which, motor planning ability, motor skills, and even motor imagery ability demonstrate prominent developmental changes (e.g., Caeyenberghs et al., 2009; Jongbloed-Pereboom et al., 2013; Smits-Engelsman & Wilson, 2013; Souto et al., 2020). Studies investigating motor process involvement in motor imagery tasks report that younger children's motor imagery is more likely to be guided by motor processes (e.g., Funk et al., 2005), which accords with the Piagetian theory arguing that the role of motor processes in cognitive development decreases as a function of age. In contrast, studies suggest that motor processes are more prominent in adolescents (e.g., Conson et al., 2013). But few studies have explicitly examined the precise relationship between motor processes and motor imagery, particularly internal motor imagery in children. Hence, the second goal of the present study was to explore whether and how the development of internal motor imagery correlates with the development of motor inhibition.

In the present study, we used a hand laterality judgment task and an alphanumeric rotation task to assess KMI and VMI, respectively. The mental rotation task is a well-established paradigm to study the cognitive process of mentally rotating objects (Shepard & Metzler, 1971). A variation of the classical mental rotation task, for example, a hand laterality judgment task, is often used to elicit KMI (e.g., de Lange et al., 2008; Parsons, 1994). In this task, participants are required to decide whether the depicted hand stimulus is a left or a right hand by pressing one of two buttons as fast as possible (de Lange et al., 2006; Parsons, 1994; Shenton et al., 2004; ter Horst et al., 2010). The hand stimuli are displayed in different angles of rotation and different directions, or different orientations (palm view or back view). Usually, response accuracy and RT are used as outcome measures. Response accuracy is indicative of the ability to solve the task correctly. Meanwhile, RT is indicative of the time spent in mentally rotating the hand stimuli back to the canonical orientation (i.e., the fingers pointing up), where the time increases with the deviation from the canonical orientation, which is taken as an indicator that participants use mental rotation to solve the task (Spruijt et al., 2017; Tomasino & Gremese, 2016). Moreover, mental rotation of object-related stimuli (e.g., three-dimensional objects or alphanumeric characters) is used to elicit VMI as well (e.g., Osuagwu & Vuckovic, 2014; Williams et al., 2006). Studies show that rotation of nonbody stimuli activate different neural areas from those activated by the rotation of hands (e.g., Kosslyn et al., 1998). Importantly, in the current study, we only presented single hands in a back view, following Williams et al. (2006).

To measure motor inhibition, a stop signal task and/or a go/no-go task are commonly used (Logan & Cowan, 1984; Tiego et al., 2018). In the go/no-go paradigm, participants are presented with a series of stimuli and are required to respond when a go stimulus is presented and to withhold their response when a no-go stimulus is presented. In this task, a no-go stimulus is usually presented with a low probability (e.g., 25%), where inhibiting a prepotency towards response execution at a preparatory or early activation stage is likely to occur. In the stop-signal paradigm, participants are required to respond to a go task as quickly as possible but inhibit their response to the go task when it is followed by an occasional stop signal. That is, the response is typically on its way to execution, but with low stop probability due to a greater demand on task inhibition processes (Johnstone et al., 2007). Researchers also assume that the motor inhibition in the go/no-go task is more likely to be automatic, which is more likely a reflection of associative learning, while the motor inhibition in stop-signal task is more likely to be controlled (Verbruggen & Logan, 2008). According to the functional equivalence hypothesis and the motor-cognitive model, the motor inhibition involved in motor imagery might be more demanding and require greater control, thus, using a stop-signal task would be more appropriate.

Previous studies reported that children around 7 years old were able to perform internal motor imagery (Spruijt et al., 2015). In addition, children aged from 5 to 12 years old demonstrated an intensive development of motor inhibition (Šimleša & Cepanec, 2015). Thus, we recruited children aged from 7 to 11 years old. We employed a child-friendly stop-signal task to measure motor inhibition, which is well examined and validated in cognitive development and individual differences research (Khng & Lee, 2014; Verbruggen et al., 2013). Thus, we set out to investigate the development of internal motor imagery, and based on it, to further clarify the link between internal motor imagery and motor inhibition in children aged from 7 to 11 years old. Based on previous findings, we expected that internal motor imagery and motor inhibition abilities would improve with age. Furthermore, since evidence shows that KMI is rated as more difficult to mobilize than other types of imagery, perhaps motor inhibition would be more likely to be involved in KMI. Alternatively, if KMI requires more effort for mobilization, children might employ the VMI strategy across the two tasks, leading to a statistically significant correlation between motor imagery and motor inhibition in both tasks, and such a link might change as a function of age.

METHODS

Participants and Procedure

First, 90 right-handed children participated the experiment. Seventeen children were excluded from the analysis because of missing data (seven from the 7-year-old group, three from the 9-year-old group, and seven from the 11-year-old group) in either task. Thus, the final sample size was 73, including 23 from the 7-year-old group (11 females, age = 7.62 ± 0.51 years; 12 males, age = 7.43 ± 0.37 years), 27 from the 9-year-old group (14 females, age = 9.47 ± 0.48 years; 13 males, age = 9.33 ± 0.35 years), and 23 from the 11-year-old group (11 females, age = 11.42 ± 0.28 years; 12 males, age = 11.58 ± 0.34 years). Children were recruited from a primary school in Hangzhou, China. All participants were in good health, with normal or corrected-to-normal vision. They were asked to report their handedness before they performed the tasks. All of them were from upper-middle-income families. The study was approved by the ethical committee of Zhejiang University, and a written consent form was obtained from parents and teachers for all of the participants.

Measures

All the children performed three tasks, including two mental rotation tasks and a motor inhibition task. The tasks were programmed in E-Prime 2.0 (Psychology Software Tools, INC.). Children were tested on a laptop with a resolution of 1024 × 768 px and a 14 in. TFT display in a one-to-one setting. All the tasks are described below.

HAND LATERALITY JUDGMENT TASK

In this task, stimuli were left or right hands portrayed from the back at 0 °, 45 °, 90 °, 135 °, and 180 °. Children were seated in front of the screen, with both hands straight in front of them, each hand resting on a key. The children were asked to determine whether pictures that appeared on the screen were left or right hands and to press the corresponding key as quickly as possible. They were observed by an experimenter to ensure they remained still except pressing the key throughout the task. There were 20 practice trials and 80 test trials (5 angles × 2 hands) in total. Accuracy and RT were recorded.

ALPHANUMERIC ROTATION TASK

In this task, an uppercase *F* or the number 5 were presented randomly in either normal or mirror-reversed orientation at five different angles, 0 °, 45 °, 90 °, 135 °, and 180 °. Participants were instructed to decide whether the stimulus was the correct or the wrong way around by press one or another key. There were 20 practice trials and 80 test trials (5 angles × 2 orientations) in total. Accuracy and response time were recorded.

STOP-SIGNAL TASK

A child-friendly stop-signal task was used. The go stimuli in this stop-signal task comprised of a strawberry and a peach (150 × 150 px in size), and the stop trials consisted of an apple of the same size.

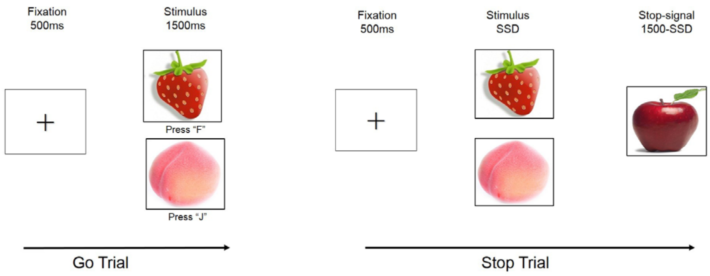

FIGURE 1.
The protocol of the go trial and stop trial in the stop-signal task.

Participants were instructed to press *F* when a strawberry appeared, and J when a peach did (go-trials), but they had to inhibit their response when an apple appeared shortly after the presentation of the go-stimulus (stop trial). Each trial began with a fixation cross lasting for 500 ms, followed by a go stimulus lasting for 1500 ms in the case of go trials. For stop trials, the stop-signal delays (SSD), the time between the go stimulus onset and stop-signal onset, were set to 100 ms, 200 ms, 300 ms, and 400 ms. The stop-signal was displayed for a maximum of 1500 ms (see Figure 1). There was one practice block (40 trials) and four test blocks in total. Each test block included 80 trials and 25% of the trials were stop-trials. The stop-trials were presented at random positions throughout each block and were counterbalanced among the four SSDs. For the dependent variable, we used the stop-signal response time (SSRT), which was calculated by subtracting the mean SSD from the |n|th RT (the integration method, Verbruggen et al., 2013).

Data Analysis

For each child in each task, mean RT and accuracy (percentage of correct responses) were calculated for each angle in the mental rotation tasks. To remove anticipatory and abnormally delayed responses, response times shorter than 250 ms and longer than 2.5 times the mean RT for each angle for each participant were excluded from analysis (Kosslyn et al., 1998).

To test the developmental change of motor imagery, we ran a set of mixed ANOVAs for accuracy score and RT of correct responses using age group (7-year-olds, 9-year-olds, and 11-year-olds) and gender (male and female) as between-subjects factors, and angle (0 °, 45 °, 90 °, 135 °, 180 °) as the within-subjects factor.

As the slope of mental rotation tasks was considered to be a key measure of the mental rotation process (Badets et al., 2013; Shepard & Cooper, 1982; Toussaint et al., 2013), we computed each participant's slope of the linear function between RTs and rotation angles for the two mental rotation tasks. Individual regression slopes were then analyzed using a 3 (age group: 7-year-olds, 9-year-olds, and 11-year-olds) × 2 (gender: male and female) ANOVA.

For the stop-signal task, SSRT was computed and then analyzed by using a 3 (age: 7-year-olds, 9-year-olds, and 11-year-olds) × 2 (gender: male and female) × 4 (SSD: 100 ms, 200 ms, 300 ms, 400 ms) repeated-measures ANOVA.

SPSS 24.0 was used to analyze the data. For all the ANOVAs, homogeneity and sphericity tests were conducted, and Greenhouse-Geisser correction was employed when necessary. The Bonferroni method was executed to conduct all the multiple comparisons, corrected alphas were provided in the Results section as well. The *p* value we report in the Results section is corrected, which was compared with .05 directly.

To clarify whether participants employed the KMI, we ran paired-samples t tests to compare the overall RT and RTs for each rotation angle of the two mental rotation tasks in each age group.

Given our study aims to investigate the relationship between motor imagery and motor inhibition, Spearman's correlations between the efficiency of motor inhibition and the individual slope of the two mental rotation tasks was calculated within each age group (Pfister et al., 2013; Toussaint et al., 2013). The Fisher's *r*-to-*Z* transformation was used to test the difference between the correlation coefficients obtained for the three age groups

RESULTS

Hand Laterality Judgment Task

For RTs, descriptive data for all angles and groups are provided in Table 1. The main effect of age was significant, $F(2, 67) = 4.59$, $p = .014$, $\eta_p^2 = .12$. The multiple comparisons (Bonferroni corrected $\alpha = .017$) showed that RTs for 7-year-olds were significantly longer than that for both 9-year-olds ($t = 2.59$, $p = .042$, $d = 0.71$) and 11-year-olds ($t = 2.75$, $p = .023$, $d = 0.80$). No significant difference was detected between 9-year-olds and 11-year-olds ($t = 0.26$, $p = 1.000$, $d = 0.10$). A significant main effect of angle was observed, $F(4, 268) = 29.69$, $p < .001$, $\eta_p^2 = .31$, suggesting that RT increased with rotation angles expanded(Bonferroni corrected $\alpha = .005$). Multiple comparisons showed that RT at 0 ° was significantly shorter than that at 90 ° ($t = 3.97$, $p = .002$, $d = 0.46$), 135 ° ($t = 5.65$, $p < .001$, $d = 0.64$), and 180 ° ($t = 8.17$, $p < .001$, $d = 0.93$), RT at 45 ° was significantly shorter than that at 90 ° ($t = 5.02$, $p < .001$, $d = 0.57$), 135 ° ($t = 6.30$, $p < .001$, $d = 0.71$), and 180 ° ($t = 8.24$, $p < .001$, $d = 0.93$), RT at 90 ° was significantly shorter than that at 180 ° ($t = 6.30$, $p < .001$, $d = 0.53$), and that RT at 135 ° was significantly shorter than that at 180 ° ($t = 4.62$, $p = .045$, $d = 0.36$). No other significant differences were detected. The main effect of gender was not statistically significant, $F(1, 67) = 1.83$, $p = .179$, $\eta_p^2 = .03$. None of the interaction effects

TABLE 1.

Comparison of Mean Response Time (ms) for the Hand Laterality Judgment Task and Alphanumeric Rotation Task

Group	Angle	Hand Laterality Judgment Task		Alphanumeric Rotation Task		t	p
		M	*SD*	*M*	*SD*		
7-year-olds	0 °	2858.28	939.62	1666.32	653.01	4.86	< .001
	45 °	2744.74	817.85	1788.41	653.02	4.64	< .001
	90 °	3239.62	1052.52	1939.76	729.33	4,45	< .001
	135 °	3341.26	1067.53	1985.79	900.39	5.26	< .001
	180 °	3582.75	1196.88	2230.15	897.56	4.86	< .001
	Overall	3126.91	885.30	1899.75	653.51	5.63	< .001
9-year-olds	0 °	2367.81	849.87	1353.76	385.39	5.94	< .001
	45 °	2351.44	934.46	1519.42	473.32	4.83	< .001
	90 °	2540.37	918.71	1564.23	416.00	5.72	< .001
	135 °	2585.63	931.28	1796.53	658.91	4.84	< .001
	180 °	2789.97	972.29	2031.50	746.59	3.62	< .001
	Overall	2521.06	828.83	1614.32	447.86	5.94	< .001
11-year-olds	0 °	2083.48	698.62	1208.82	597.63	6.26	< .001
	45 °	2164.06	781.32	1353.51	750.62	4.31	< .001
	90 °	2427.00	986.14	1604.89	746.23	5.03	< .001
	135 °	2750.06	1109.82	1668.02	724.61	6.74	< .001
	180 °	2981.14	996.67	2053.70	987.03	4.75	< .001
	Overall	2437.80	841.24	1546.97	678.42	6.17	< .001

between angle and age, $F(8, 268) = 1.65$, $p = .11$, $\eta_p^2 = .05$, between age and gender, $F(2, 67) = 1.06$, $p = .35$, $\eta_p^2 = .03$, between angle and gender, $F(4, 268) = 0.56$, $p = .67$, $\eta_p^2 = .01$, and between angle, age, and gender, $F(8, 268) = 0.75$, $p = .63$, $\eta_p^2 = .02$, were detected (see Figure 2, Panel A).

For accuracy scores, the main effect of age was significant, $F(2, 67) = 9.82$, $p < .001$, $\eta_p^2 = .23$, suggesting accuracy scores increased with age (7-year-olds = 70 ± 3%, 9-year-olds = 75 ± 3%, 11-year-olds = 90 ± 3%). Multiple comparisons (Bonferroni corrected $\alpha = .017$) showed that 11-year-olds performed significantly better than 7-year-olds ($t = 4.26$, $p < .001$, $d = 1.42$) and 9-year-olds ($t = 3.25$, $p = .006$, $d = 1.01$), but no significant difference was detected between 7-year-olds and 9-year-olds ($t = 1.23$, $p = 0.686$, $d = 0.45$). The main effect of angle was also significant, $F(4, 268) = 8.68$, $p < .001$, $\eta_p^2 = .12$, showing that the accuracy scores significantly decreased with the angles (0 ° = 82 ± 2%, 45 ° = 82 ± 2%, 90 ° = 79 ± 2%, 135 ° = 77 ± 3%, 180 ° = 73 ± 2%). Pairwise comparisons (Bonferroni corrected $\alpha = .005$) showed that accuracy scores at 135 ° were significantly lower than at 0 ° ($t = 2.95$, $p = .037$, $d = 0.36$), accuracy scores at 180 ° were significant lower than at 0 ° ($t = 4.68$, $p < .001$, $d = 0.56$) and 45 ° ($t = 4.53$, $p < .001$, $d = 0.56$). No other differences were detected. The main effect of gender was not statistically significant, $F(1, 67) = 0.011$, $p = .916$, $\eta_p^2 < .01$. None of the interaction effects between angle and age, $F(8, 268) = 0.62$, $p = .743$, $\eta_p^2 = .02$, between age and gender, $F(2, 67) = 0.48$, $p = .619$, $\eta_p^2 = .03$, between angle and gender, $F(4, 268) = 1.50$, $p = .207$, $\eta_p^2 = .02$, or between angle, age, and gender, $F(8, 268) = 1.34$, $p = .229$, $\eta_p^2 = .04$, were significant (see Figure 3, Panel A).

An analysis of individual regression slopes revealed that the main effect of age was not statistically significant, $F(2, 67) = 2.99$, $p = .057$, $\eta_p^2 = .08$, but the slope increased from 7-year-olds (201 ms/45 °) to 9-year-olds (112 ms/45 °) and 11-years-olds (219 ms/45 °), showing an increasing trend with age. No statistically significant main effect of gender was detected, $F(1, 67) = 0.88$, $p = .350$, $\eta_p^2 = .01$.

Alphanumeric Rotation Task

For RT, descriptive data for all angles and groups are provided in Table 1. The main effect of age was not statistically significant, $F(2, 67) = 1.97$, $p = .147$, $\eta_p^2 = .06$. A significant main effect of angle was observed, $F(4, 268) = 33.29$, $p < .001$, $\eta_p^2 = .33$, suggesting that RTs increased with rotation angles. Pairwise comparisons (Bonferroni corrected $\alpha = .005$) showed that RTs at 0 ° were significantly shorter than at 45 ° ($t = 3.58$, $p = .006$, $d = 0.42$), 90 ° ($t = 5.71$, $p < .001$, $d = 0.67$), 135 ° ($t = 6.37$, $p < .001$, $d = 0.76$), and 180 ° ($t = 9.23$, $p < .001$, $d = 1.09$), RTs at 45 ° were significantly shorter than at 135 ° ($t = 3.91$, $p = .002$, $d = 0.46$) and 180 ° ($t = 6.95$, $p < .001$, $d = 0.82$), RTs at 90 ° were significantly shorter than at 180 ° ($t = 5.66$, $p < .001$, $d = 0.67$), and that RTs at 135 ° were significant shorter than at 180 ° ($t = 3.92$, $p = .002$, $d = 0.45$). No other statistically significant differences were detected. The main effect of gender was not statistically significant, $F(1, 67) = 0.05$, $p = .826$, $\eta_p^2 = .001$. None of the interaction effects between angle and age, $F(8, 268) = 0.76$, $p = .605$, $\eta_p^2 = .02$, between age and gender, $F(2, 67) = 0.48$, $p = .619$, $\eta_p^2 = .01$, between angle and gender, $F(4, 268) = 0.34$, $p = .808$, $\eta_p^2 = .005$, or between angle, age and gender, $F(8, 268) = 1.80$, $p = .098$, $\eta_p^2 = .05$, were significant (see Figure 2, Panel A).

For accuracy scores, the main effect of age was significant, $F(2, 67) = 6.73$, $p = .002$, $\eta_p^2 = .17$, suggesting accuracy scores increased with age (7-year-olds = 73 ± 3%, 9-year-olds = 75 ± 3%, 11-year-olds = 88 ± 3%). Specifically, 11-year-olds performed significantly better than 7-year-olds ($t = 3.31$, $p = .004$, $d = 1.04$) and 9-year-olds ($t = 3.02$, $p = .01$, $d = 0.87$), but no significant difference was detected between 7-year-olds

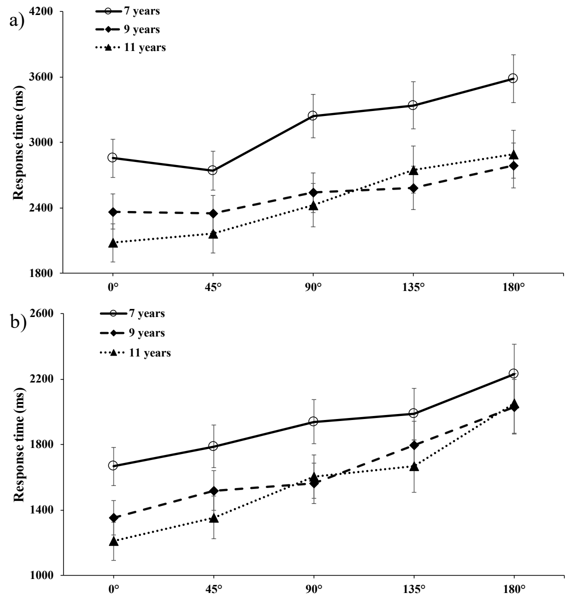

FIGURE 2.

Mean response time (ms) in the Hand Laterality Judgment Task (Panel A) and the Alphanumeric Rotation Task (Panel B) as a function of age (7, 9, and 11) and stimulus rotation angle (0 °, 45 °, 90 °, 135 °, 180 °). Error bars indicate the *SEM*.

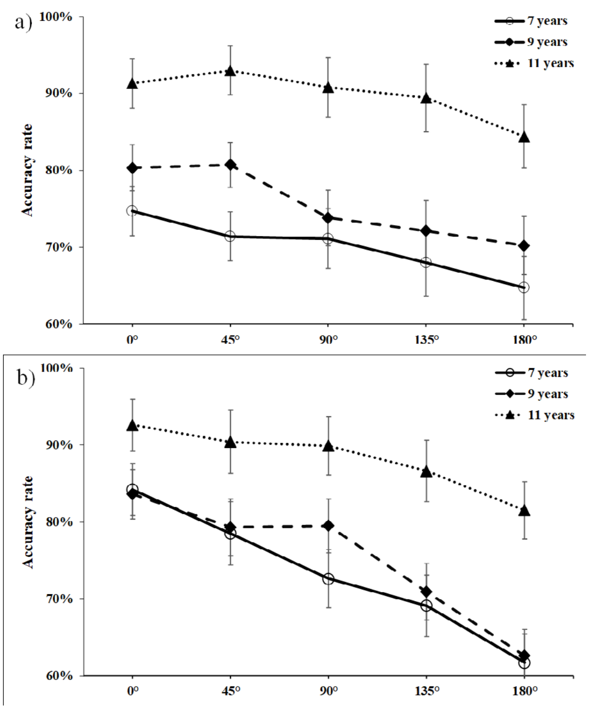

FIGURE 3.

Mean accuracy in the Hand Laterality Judgment Task (Panel A) and the Alphanumeric Rotation Task (Panel B) as a function of age (7, 9, and 11) and stimulus rotation angle (0 °, 45 °, 90 °, 135 °, 180 °). Error bars indicate the *SEM*.

and 9-year-olds. The main effect of angle was also significant, $F(4, 268) = 27.12$, $p < .001$, $\eta_p^2 = .29$, showing that accuracy scores significantly decreased as the rotation angle increased (0 ° = 87 ± 2%, 45 ° = 83 ± 2%, 90 ° = 80 ± 2%, 135 ° = 76 ± 3%, 180 ° = 67 ± 2%). Pairwise comparisons (Bonferroni corrected α = 0.005) showed that accuracy at 0 ° was significantly higher than at 90 ° ($t = 3.39$, $p = .013$, $d = 0.39$), 135 ° ($t = 6.59$, $p < 0.001$, $d = 0.76$), and 180 ° ($t = 8.62$, $p < .001$, $d = 1.02$), accuracy at 45 ° was significantly higher than at 135 ° ($t = 4.00$, $p = .002$, $d = 0.48$) and 180 ° ($t = 5.83$, $p < .001$, $d = 0.72$), accuracy at 90 ° was significant higher than at 135 ° ($t = 3.00$, $p = .032$, $d = 0.37$) and 180 ° ($t = 5.71$, $p < .001$, $d = 0.69$), and that accuracy at 135 ° was significant higher at 180 ° ($t = 3.40$, $p = .013$, $d = 0.41$). No other differences were detected. The main effect of gender was not statistically significant, $F(1, 67) = 0.003$, $p = .959$, $\eta_p^2 < .01$. None of the interaction effects between angle and age, $F(8, 268) = 1.43$, $p = .195$, $\eta_p^2 = .04$, between age and gender, $F(2, 67) = 1.98$, $p = .146$, $\eta_p^2 = .06$, between angle and gender, $F(4, 268) = 0.33$, $p = .829$, $\eta_p^2 = .01$, or among angle, age, and gender, $F(8, 268) = 1.03$, $p = .410$, $\eta_p^2 = .03$, were significant (see Figure 3, Panel B).

An analysis of individual regression slopes revealed that the main effect of age was not statistically significant, $F(2, 67) = 1.45$, $p = .242$, $\eta_p^2 = .04$, but the slope increased from 7-year-olds (127 ms/45 °) to 9-year-olds (157 ms/45 °), and 11-years-olds (201 ms/45 °), showing an increasing trend with age. No statistically significant main effect of gender was detected, $F(1, 67) = 0.12$, $p = .732$, $\eta_p^2 = .54$, and no significant interaction effect between gender and age was detected, $F(2, 67) = 0.62$, $p = .539$, $\eta_p^2 = .02$.

A comparison of the overall RT and RTs for each angle in each task was conducted by a paired-samples *t* test. The results showed that overall mean RT for the hand laterality judgment task was significantly longer than that for alphanumeric rotation task, $t(22) = 5.63$, $p < .001$, $d = 1.17$; $t(26) = 5.94$, $p < .001$, $d = 1.14$; $t(22) = 6.17$, $p < .001$, $d = 1.29$. All the other comparisons were significant (*ps* < .001, see Table 1).

Stop-Signal Task

Descriptive data of this task for all groups are provided in Table 2.

The main effect of age was significant, $F(2, 67) = 6.86$, $p = .002$, $\eta_p^2 = .17$. A significant difference was detected between SSRT for 7-year-olds and 9-year-olds ($t = 2.59$, $p = .035$, $d = 0.68$), as well as 7-year-olds and 11-year-olds ($t = 3.61$, $p = .001$, $d = 1.41$). No significant differences were detected between SSRT for 9-year-olds and 11-year-olds ($t = 1.16$, $p = .249$, $d = 0.33$). A significant main effect of SSD was detected, $F(3, 201) = 26.12$, $p < .001$, $\eta_p^2 = .28$. Pairwise comparisons (Bonferroni corrected α = 0.008) indicated that the SSRT at 100 ms SSD was significantly longer than at 200 ms SSD ($t = 5.26$, $p < .001$, $d = 0.62$), at 300 ms SSD ($t = 6.67$, $p < .001$, $d = 0.80$), and at 400 ms SSD ($t = 9.70$, $p < .001$, $d = 1.13$). No other statistically significant effects were detected. No main effect of gender was detected, $F(1, 67) = 0.002$, $p = .960$, $\eta_p^2 < .001$. The interaction effects between age and SSD, $F(6, 201) = 0.69$, $p = .637$, $\eta_p^2 = .02$, the between gender and SSD, $F(3, 201) = 0.67$, $p = .555$, $\eta_p^2 = .01$, between age and gender, $F(2, 67) = 0.36$, $p = .703$, $\eta_p^2 = .01$, and between SSD, age, and gender, $F(6, 201) = 1.76$, $p = .119$, $\eta_p^2 = 0.05$, were not statistically significant (see Figure 4).

Relationship Between Internal Motor Imagery and Motor Inhibition

There was no significant Spearman's correlation between motor inhibition and the slopes of the two rotation tasks for all the groups (see Table 3).

Moreover, the Fisher's *r*-to-*Z* transformation for the hand laterality judgment task showed that a significant difference existed between 7- and 9-year-olds ($Z = 2.46$, $p < .001$, $q = 0.71$), and no difference was detected between 7- and 11-year-olds ($Z = 1.21$, $p = .110$, $q = 0.32$), and 9- and 11-year-olds ($Z = -1.19$, $p = .124$, $q = 0.38$). These results suggest that the difference between 7- and 9-year-olds in KMI might be due to the capacity to engage in motor inhibition.

For the alphanumeric rotation task, the Fisher's *r*-to-*Z* transformation showed no significant difference between 7- and 9-year-olds ($Z = 0.42$, $p = .332$, $q = 0.21$), 7- and 11- year-olds ($Z = 0.5$, $p = .314$, $q = 0.27$), or 9- and 11-year-olds ($Z = -1.09$, $p = .138$, $q = 0.49$). These results suggest that better motor inhibition was associated with the higher slope values in the three age groups considered in the present study.

DISCUSSION

The main objective of the present study was to investigate the link between internal motor imagery ability and motor inhibition in school-aged children and how this link differs across age. First, the mean accuracy of both mental rotation tasks across all age groups was

TABLE 2.
Children's Performance in the Stop-Signal Task

Group	SSD (ms)	Go ACC	M of Go RT (ms)	SSRT (ms)	Probability of responding on Stop trials
7-year-olds	100	0.88 (0.11)	836.05 (120.45)	424.33 (108.08)	0.08 (0.14)
	200			358.46 (131.44)	0.11 (0.15)
	300			326.03 (81.94)	0.18 (0.18)
	400			306.59 (58.70)	0.34 (0.17)
	Overall			353.85 (43.32)	0.16 (0.13)
9-year-olds	100	0.90 (0.11)	763.81 (122.71)	379.72 (87.30)	0.06 (0.14)
	200			289.91 (127.25)	0.10 (0.18)
	300			298.20 (81.29)	0.22 (0.20)
	400			295.23 (73.13)	0.41 (0.22)
	Overall			315.76 (66.13)	0.17 (0.11)
11-year-olds	100	0.96 (0.05)	771.29 (103.90)	377.78 (54.35)	0.02 (0.67)
	200			283.77 (60.96)	0.02 (0.49)
	300			268.44 (61.47)	0.13 (0.16)
	400			263.76 (58.71)	0.30 (0.20)
	Overall			298.44 (35.04)	0.11 (0.10)

Note. SSD = stop-signal delay; ACC = accuracy; SSRT = stop-signal response time. *SD*s are given in brackets.

above 65%. This indicated that children can identify the direction of depicted body or nonbody stimuli accurately, and thus have the ability to solve the task (e.g., Frick et al., 2013; Spruijt et al., 2015). In addition, the RT for both the hand laterality judgment task (a task associated with KMI) and the alphanumeric rotation task (assessing VMI) of all age groups showed a typical pattern, that is, our results replicated the positive linear relation between RT and angular disparity. This finding was in line with other studies employing the same tasks and the same stimulus orientation in children at school age (e.g., Caeyenberghs et al., 2009; de Lange et al., 2006; Funk et al., 2005; Spruijt et al., 2015; ter Horst et al., 2010; Williams et al., 2006). Moreover, a comparison of the RT for the hand laterality judgment task and the alphanumeric rotation task across angles showed that the former was significantly longer than the latter. Since the time taken to perform a mental task is an index of the cognitive processes underlying that mental task, a higher time requirement in the hand laterality judgment task might suggest the use of a KMI strategy (Jeannerod, 1997; McAvinue & Robertson, 2008).

Regarding the age-related differences, we found that the performance in both rotation tasks was better in the older age group than the younger age group. This provided further evidence that internal imagery develops during this five-year period (Caeyenberghs et al., 2009; Smits-Engelsman & Wilson, 2013; Spruijt et al., 2015; Spruijt et al., 2017). Moreover, our results are in line with the developmental trend reported in external motor imagery ability research (Gabbard et al., 2012; Hoyek et al., 2009). Although researches demonstrated that internal imagery develops before external imagery, whether children in our study had achieved a mature response pattern of internal motor imagery needs further elucidation (Estes, 1998; Toussaint et al., 2013)

Notably, our results did not show significant gender differences. This is in line with several studies conducted in typically developing children which reported no gender differences regarding the general ability to form mental images (Munroe-Chandler, Hall, Fishburne, & Hall, 2007; Munroe-Chandler, Hall, Fishburne, & Strachan, 2007). Research suggests that children's mental rotation ability is affected by their academic programs and spatial activity experiences (e.g., Habacha et al., 2014; Logie et al., 2011; Pietsch & Jansen, 2012). Our population consisted of typically developing children from predominantly privileged backgrounds, where girls and boys are receiving the same education, which might lead to their comparable performance across tasks. But in another study, Hoyek et al. (2009) recruited 8- to 12-year-olds to imagine performing a sequence of different motor tasks. They found that boys outperformed girls in imagery performance, and speculated that boys might be able to form more accurate mental images in real-time due to their higher visuo-spatial ability. Whether or not children's imagery performance is influenced by their spatial abilities is hard to determine in our data.

Motor inhibition ability can be reflected through the SSRT in the stop-signal task, specifically, a short SSRT suggests a high efficiency in motor inhibition. The SSRT in the present study decreased when SSD increased. This was consistent with previous findings (Verbruggen et al., 2013). Meanwhile, SSRT decreased from 7-year-olds to 11-year-olds, suggesting that there is an improvement of motor inhibition ability in school-aged children, and confirming similar findings from studies using the stop-signal task or other tasks (Chevalier et al., 2012; Davidson et al., 2006). However, a significant SSRT difference was only detected between 7-year-olds and 9-year-olds and 7-year-olds and 11-year-olds but not between 9-year-olds and 11-year-olds. A possible reason might be that inhibitory control develops rapidly during the first two years of formal schooling, and then demonstrates a slower increase rate (Sadeghi et al., 2020). Another possible explanation could be that the same task may not be developmentally appropriate for all ages (Petersen et al., 2016). Alternative tasks, such as the go/no-go task, flanker task, circle-tracing task, and so forth would allow us to accommodate developmental changes in the manifestation of motor inhibition (Sadeghi et al., 2020).

Regarding the relationship between internal motor imagery and motor inhibition, no correlation between performance of hand laterality judgment task and stop-signal task was found. Our results

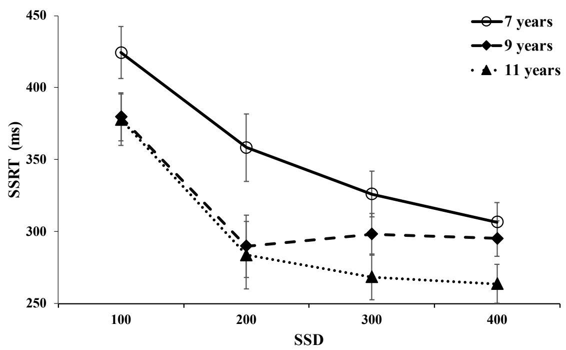

FIGURE 4.
The stop-signal response time (SSRT) in the stop-signal task as a function of age (7, 9, and 11) and stop-signal delay (*SD*, 100, 200, 300, and 400 ms). Error bars indicate the *SEM*.

TABLE 3.
Spearman's Correlation Between Inhibition Efficiency (SSRT) and the Slopes of the Hand Laterality Judgment Task and Alphanumeric Rotation Task

Task by age groups	Correlation coefficients	p
Hand Laterality Judgment Task		
7-year-olds	0.39	.06
9-year-olds	−0.29	.15
11-year-olds	0.09	.67
Alphanumeric Rotation Task		
7-year-olds	−0.15	.49
9-year-olds	−0.35	.07
11-year-olds	0.12	.59

suggest that both children's abilities of internal motor imagery and motor inhibition refine as they develop, but whether motor inhibition is involved in internal KMI needs further investigation. Fisher's r-to-Z transformation was further used to test the difference between the correlation coefficients obtained for three age groups. We found a significant difference between 7- and 9-year-olds in the relation between the hand laterality judgment task performance and the stop signal task performance, that is, the relation between KMI and motor inhibition decreases from 7-year-olds to 9-year-olds. This suggest that the involvement of motor inhibition in internal motor imagery might change with age. However, we failed to find any other significant age differences regarding the relation between the alphanumeric rotation task performance and the stop signal task performance. Our results are in line with previous findings suggesting that the hand laterality judgment task is more strongly associated with cognitive control of action (Caeyenberghs et al., 2009; Graybiel, 2000). As the RTs for the hand laterality judgment task are longer than that for the alphanumeric rotation task, our results suggest that children were relying on different strategies to perform the two tasks, which could be a possible reason for the dissociation of the motor inhibition involvement in KMI and VMI (McAvinue & Robertson, 2008). But whether the KMI and internal VMI have different developmental trajectories since childhood needs further investigation (Casey et al., 2005; Guillot et al., 2009; Jiang et al., 2015).

Limitations

Several limitations of this study should be noted. First, an increased RT and/or decreased response accuracy when mentally rotating lateral (rotation angles between 180 ° and 360 °) compared to medial (rotation angles between 0 ° and 180 °) hand stimuli, as well as an increased RT and/or decreased response accuracy when the participants' hand orientation is incongruent with the orientation of the depicted hand would both help us capture children's employment of KMI (de Lange et al., 2006; Shenton et al., 2004; ter Horst et al., 2010). Moreover, KMI is rated as more difficult to mobilize than other types of imagery. Even if children have received specific instructions and understood the difference between KMI and VMI, it is still difficult to dissociate KMI and VMI (Guillot et al., 2009). Using both physiological measures from the autonomic neural system and the motor imagery questionnaire, the assessment quality of motor imagery would most likely to be improved (Guillot et al., 2009; Martini et al., 2016).

Second, we observed relatively small effects in the correlation analysis. A possible reason might be that typically developing children did not provide sufficient information about the relation between motor imagery and motor inhibition. Future studies should consider recruiting children with developmental coordination disorders and cerebral palsy, showing deficiency in both rapid online movement control and motor imagery, to further reveal the involvement of motor inhibition in the process of motor imagery (Adams et al., 2014; Hyde & Wilson, 2011a, 2011b; Wilson et al., 2013; Wolpert, 1997).

Another caveat that might impede the generalization of our results is the cross-sectional study design, which could not demonstrate whether there is any causal effect between internal motor imagery and motor inhibition and show how the associations in the present study may change over time. Overall, future studies with a longitudinal design, more representative samples, and a more comprehensive measurement of motor imagery would allow us to explore the cognitive processes involved between internal motor imagery and motor inhibition.

CONCLUSIONS

To conclude, our work provides further evidence for the development of internal motor imagery and motor inhibition abilities, illustrating progressive development characteristics in school aged children. Specifically, our results suggest that typically developing children at 7 years old are able to use internal motor imagery. Moreover, the difference of the relation between internal motor imagery and motor inhibition between 7- and 9-year-olds suggests this age range is be a sensitive window to explore the involvement of motor inhibition in internal motor imagery processes. Our work provides support for potential application of incorporating internal motor imagery training in rehabilitation protocols in children.

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