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ORIGINAL ARTICLE

# The relation between measures of cognitive and motor functioning in 5- to 6-year-old children

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**Abstract** Specific relations between executive functions (working memory capacity, planning and problem-solving, inhibitory control) and motor skill performance (anticipatory motor planning, manual dexterity) were examined in 5- to 6-year-old children ($N = 40$). Results showed that the two motor skill components were not correlated. Additionally, it was found that response planning performance was a significant predictor of anticipatory motor planning performance, whereas inhibitory control and working memory capacity measures were significant predictors of manual dexterity scores. Taken together, these results suggest that cognitive and motor skills are linked, but that manual dexterity and anticipatory motor planning involve different specialized skills. The current study provides support for specific relations between cognitive and motor performance, which has implications for early childhood cognitive-motor training and intervention programs.

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## Introduction

Although often examined separately, the importance of motor skill proficiency to perceptual and cognitive performance has long been acknowledged by psychologists (e.g., Edelman, 1987, 1989; Piaget, 1952; Weimer, 1977). The link between global motor and cognitive performance is supported by neuroimaging and neuroanatomical studies indicating that cognitive and motor skills share overlapping neural mechanisms and draw on common resources (e.g., Diamond, 2000; Michel, Roethlisberger, Neuenschwander & Roebers, 2011; Miyake et al., 2000; Piek, Dyck, Francis & Conwell, 2007; Sergeant, 2000). Further indirect evidence for this link comes from behavioral studies demonstrating that children with developmental disorders (e.g., attention deficit hyperactivity disorder [ADHD], Eliasson, Rosblad & Forssberg, 2004, Fliers et al., 2008, Pennington & Ozonoff, 1996; developmental coordination disorder [DCD], Alloway & Temple, 2007, Piek et al., 2007) consistently obtain lower scores on tests of motor coordination (Kaplan, Wilson, Dewey & Crawford, 1998; Piek, Pitcher & Hay, 1999), motor inhibition (Michel et al., 2011; Sergeant, 2000), and working memory (Pennington & Ozonoff, 1996; Piek et al., 2007).

Although this corpus of research indicates that there is a strong, albeit indirect, link between global cognitive functions and motor skills, studies that directly tested the relation between global aspects of motor skill and cognitive performance have reported only weak associations between these two processes (Roebers & Kauer, 2009; Wassenberg et al., 2005). For example, Wassenberg et al. (2005) found no relation between global aspects of cognitive and motor performance in a large sample ($n = 378$) of normally developing 5- and 6-year-old children. Furthermore, when cognitive tasks without a motor component were included in the estimate of cognitive performance, the association with overall motor performance was non-significant. Instead, a more specific association between cognitive and motor performance was supported: there were modest positive correlations between total motor performance (i.e. total score across four motor function areas [static balance, dynamic balance, ball skills, and diadochokinesis] and manual dexterity) and measures of verbal motor integration, word order, and verbal fluency. In contrast, working memory (progressive figures, number recall), passive vocabulary, and perceptual closure ability were not correlated with total motor performance.

Roebers and Kauer (2009) reported similar results in their study of 112 normally developing 7-year-old children. Controlling for age, they found significant correlations between both inhibition measures (Simon task, Flanker task) and whole body coordination (jumping, moving sideways), and between Simon task performance and whole body coordination, postural flexibility (moving from lying face down on the ground to upright stance), and manual dexterity (pegboard task). Working memory performance (Backward Color Recall task) was significantly associated with postural flexibility, but not with whole body coordination or manual dexterity. Together, their findings suggested that only some executive functions and motor control aspects are significantly interrelated.

The idea that specific relations between cognitive and motor performance exist is further supported by reports of specificity of motor skill proficiency (Drowatsky & Zuccato, 1967; Haga, Pedersen & Sigmundsson, 2008; Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Craje & Steenbergen, 2013; Lorås & Sigmundsson, 2012; Lorås, Stensdotter, Öhberg & Sigmundsson, 2013). In an early study, Drowatsky and Zuccato (1967) examined performance on six balance tasks and found that the correlations among these tasks were quite low (highest $r = 0.31$, range $= 0.03$–$0.26$), demonstrating little association even across tests derived from the same motor skill. Haga et al. (2008) investigated the interrelation among eight different motor skills (posting coins, threading beads, and bicycle trail [manual dexterity], catching bean bag, rolling ball into goal [ball skills], one-leg balance, jumping over cord, and walking with heels raised [balance]) in 91 four-year-old children. That study found relatively low correlations between individual tasks, with the highest correlation between the rolling ball into goal task (ball skills) and walking with heels raised (balance) tasks ($r = 0.614$) and the lowest correlation between the threading beads (manual dexterity) and between the rolling ball into goal (ball skills) tasks ($r = -0.005$).

Considering the literature summarized thus far it is clear that different motor skill components require very specific abilities for skillful performance and that specific associations exist between cognitive control and motor control processes. In this study we investigated specific associations between two different motor skill components (anticipatory motor planning, manual dexterity) and three executive functions (working memory, problem solving, and inhibition) in normally developing 5- to 6-year-old children. In the following sections we expound upon the three executive functions and the two motor skill components examined in this study, and the specific links between executive functions and these motor skill components. We then provide specific hypotheses regarding the relation between the two motor skill components, and the specific associations between the selected executive functions and motor control processes.

## Executive functions

The cognitive processes required for successful goal-directed behavior are referred to as executive functions, which can be considered a family of top-down mental processes required when relying on instinct would be ill-advised, insufficient, or impossible (Diamond, 2013; Espy, 2004).

Executive functions are linked to frontal structures of the brain (in particular to the dorsolateral prefrontal cortex) and cerebellum (Bernard & Seidler, 2013; Diamond, 2000; Tiemeier et al., 2010).

Working memory is a commonly examined executive function which can be defined as the collection of cognitive processes that temporarily retain information in an accessible state, suitable for carrying out any mental task (Cowan, 1998; Ozonoff & Strayer, 2001; Verté, Geurts, Roeyers, Oosterlaan & Sergeant, 2006). Working memory is involved in a number of executive or frontal lobe tasks, particularly those that are essential for the voluntary control of behavior based on internal plans. Another important executive function component is inhibitory control (e.g., Miyake et al., 2000; Zelazo, Carter, Resnick & Frye, 1997) which is important for controlling one's behavior and exercising discipline (i.e. resisting temptation to not complete a task), controlling one's attention (selective or focused), and self-regulation (controlling one's emotions so as to not act inappropriately). Response planning is a critical skill in the real word, and includes processes such as strategy formation, coordination and sequencing of mental functions, and holding information on-line. The basic abilities required for successful planning rely on other functions, such as working memory, decision-making ability, inhibitory control, flexibility, and sustained attention (Lezak, Howieson & Loring, 2004; Malloy-Diniz et al., 2008; Miyake et al., 2000).

## Links between executive functions and motor skills

One aspect of motor control that has been the center of focus in recent years is anticipatory motor planning. It is typically reported that neurologically healthy adults will grasp an object with an initial grasp posture that allows a comfortable and controllable position at the end of the movement (hereafter referred to as the *end-state comfort effect*, Rosenbaum et al., 1990). In recent years a number of researchers have sought to delineate the developmental trajectory of anticipatory motor planning (see Wunsch, Henning, Aschersleben & Weigelt, 2013 for a review). In general, it is reported that the propensity to satisfy end-state comfort improves and becomes more consistent as children age. That said, the development of anticipatory motor planning is not linear, but follows a positively accelerated function, with a noticeable growth spurt in performance when children are aged between 5 and 8 years, with anticipatory motor planning performance approaching adult levels somewhere after 10 years of age. The selection of initial grasp postures that result in end-state comfort indicate that individuals are able to formulate a plan (i.e. strategy) that integrates biomechanical and cognitive factors as well as future task demands, to monitor the task as it unfolds, and to update the plan in response to changes in the environment.

Stöckel, Hughes and Schack (2012) recently employed the Structural Dimensional Analysis-Motoric (SDA-M, Schack & Mechsner, 2006) to examine potential associations between anticipatory motor planning performance and cognitive abilities in children aged between 7 and 9 years. That study found that children with well-structured grasp representations were more likely to select end-state comfort compliant grasp postures compared to children whose cognitive representations were not structured by grasp comfort, regardless of age. The authors postulated that well-structured cognitive representations enable children to better resolve conflicts between the habitual (that favors grasps that were rewarding in the past) and goal-directed systems (that selects actions depending upon both current and future task requirements), and select end-state comfort compliant grasp postures (Herbort & Butz, 2011). The results of that study, thus, highlight that cognitive abilities play a crucial role in the planning of grasp postures, especially in developing children.

There is also indirect evidence that anticipatory motor planning and working memory draw on common resources (Logan & Fischman, 2011; Weigelt, Rosenbaum, Huelshorst & Schack, 2009). Weigelt et al. (2009) showed that reducing the effort needed for the memory task (i.e. when using free recall instead of serial recall) led to improved anticipatory motor planning performance, and that concurrent performance of a motor and memory task resulted in the elimination of the recency effect (i.e. recent items were more likely to be recalled than earlier items). Logan and Fischman (2011) extended this line of research by manipulating the difficulty of the anticipatory motor planning task, and reported an elimination of the recency effect in motor tasks that involved no or very limited motor planning. Logan and Fischman (2011) argued that the abolition of the recency effect is a basic concurrence cost of motor and memory tasks, such that the mere execution of a motor planning task leads to performance decrements in concurrent working memory tasks.

Another frequently studied aspect of motor control is manual dexterity, which is involved in everyday activities such as handwriting, cutting paper with scissors, and playing musical instruments. Manual dexterity improves with age in typically developing school age children (e.g., Hill & Khanem, 2009; Kilshaw & Annett, 1983) and is strongly associated to the size of the corpus callosum (total midsagittal cross area as well as frontal, middle, and posterior areas, Rademaker et al., 2004). Investigations have revealed that manual dexterity performance is significantly correlated with response inhibition (Livesey, Keen, Rouse & White, 2006; Michel et al., 2011). For example, Livesey et al. (2006) examined the relation between measures of response inhibition (Stroop and stop-signal task) and motor tasks in the M-ABC in 5- and 6-year-old children. The authors found that shorter Stroop task reaction times were significantly correlated with higher manual dexterity scores (with scores on the fine-motor sub-task predicting Stroop task performance), whereas throwing accuracy and balance were not.

In sum, there is evidence that different motor skill components require very specific abilities for skillful performance, and that specific associations exist between cognitive control and motor control processes. There is indirect evidence linking anticipatory motor planning and working memory performance (Logan & Fischman, 2011; Weigelt et al., 2009), and correlational studies demonstrating that manual dexterity performance is significantly associated with response inhibition (Livesey et al., 2006; Michel et al., 2011), but not working memory performance (Roebers and Kauer 2009). However, there is little direct evidence indicating which executive functions are involved in anticipatory motor planning, and whether the same executive functions are also required for skillful manual dexterity performance.

## The present study

The aim of the present paper, therefore, was to investigate specific associations between different motor skill aspects (anticipatory motor planning, manual dexterity) and three measures of executive functions (working memory, problem solving, and inhibition) in a sample of normally developing 5- and 6-year-olds. Based on previous literature demonstrating a high specificity in motor skill performance (Drowatsky & Zuccato, 1967; Haga et al., 2008) we expected no or only weak associations between anticipatory motor planning and manual dexterity. Moreover, given previous research from adult populations, it was hypothesized that anticipatory motor planning performance would be positively correlated with working memory (Logan & Fischman, 2011; Weigelt et al., 2009). It was also expected that anticipatory motor planning would be positively correlated with both problem solving and inhibitory control as the basic abilities required for successful response planning are said to draw on such processes (Lezak et al., 2004; Malloy-Diniz et al., 2008). Last, it was hypothesized that manual dexterity would be correlated with inhibitory control (Livesey et al., 2006; Michel et al. 2011), but not working memory (Michel et al., 2011; Roebers & Kauer, 2009).

## Methods

### Participants

Forty 5- to 6-year-old children (mean age = 73.5 months, SD = 5.7, 25 girls, 15 boys) participated in this experiment. The decision to examine kindergarten age children was based on the following considerations: (1) there is a major growth spurt in the development of more general cognitive functions that occurs in this age group (Bell & Livesey, 1985; Chelune & Baer, 1986), (2) fine motor skills at kindergarten entrance predict later reading and mathematics achievement (Grissmer, Grimm, Aiyer, Murrah & Steele, 2010) and are a strong predictor of kindergarten retention (when controlling for vocabulary, auditory and visual skills, and sociodemographic factors; Roth, McCaul & Barnes, 1993).

Of the forty children tested, 37 were right-handed and 3 were left-handed, as determined by the hand children used to draw a house, and to throw a ball three times. All children had normal or corrected to normal vision, and had no known neuromuscular disorders. Informed consent was obtained from the parents of the children prior to participation in the experiment. Children were recruited from two kindergartens in Rostock, Germany. The experiment was approved by the local school authorities and the institutional review board, and conformed to the declaration of Helsinki.

### Measures and procedures

The executive function components tested were working memory capacity (Corsi Block-Tapping Test, CBT), planning and problem-solving abilities (Tower of London Task, TOL), and inhibitory control (Animal Stroop task, AS). The two motor control aspects tested were anticipatory motor planning and manual dexterity. Anticipatory grasp posture planning was examined using a unimanual and bimanual bar transport task. Manual dexterity was assessed using the age-class 1 manual dexterity assessment from the Movement Assessment Battery for Children 2 (M-ABC-2). These tasks were chosen because they have been established in the developmental literature and were appropriate for children aged 5–6 years (i.e. no ceiling or floor effects for this age group).

All children were tested individually in a quiet room at their respective kindergarten. The experimenter was the same for all children. Initial pilot testing indicated that children were better able to sustain focus and concentration throughout the whole experiment when the experiment was administered by sandwiching the executive function measures between the motor tasks. As such, the tasks were administered during a 1- to 1.5-h session in the following standardized order: bar transport task, CBT, TOL, AS, and the manual dexterity assessment from M-ABC-2 for age-class 1.

#### *Bar transport task*

Anticipatory motor planning was assessed using the bar transport task (Hughes & Seegelke, 2013; Rosenbaum et al., 1990; Weigelt, Kunde & Prinz, 2006; Weigelt & Schack, 2010). The to-be manipulated objects were two wooden cylinders (22 cm in height, 2 cm in diameter) painted black on one end and white on the other end. The objects were horizontally positioned on wooden cradles (20 cm length, with 10 cm between cradles) that held the objects 25 cm above the table top. The targets were wooden cubes (10 cm in length, 10 cm in width, 10 cm in height) with a round hole in the center (2.5 cm diameter) located 10 cm in front of each object cradle.

At the start of each trial, the child stood behind the starting line (90 cm away from the table) with their hands relaxed by their sides. After receiving instructions about which end of the bar(s) to insert into the target, the child walked up to the apparatus, picked up the bar(s) and inserted the required end(s) into the target. After holding the bar at the target location for 5 s, the child placed it back onto the support cradle (with a pincer grip after releasing the bar), and walked back to the starting position. Instructions were standardized for all children and identical to that used to examine anticipatory motor planning in 3- to 5-year-olds (Weigelt & Schack, 2009), 7- to 9-year-olds (Stöckel et al., 2012) and adults (Hughes, Seegelke & Schack, 2012). Specifically, children were instructed to grasp the bar using a full power grip (instructions translated from German: "grasp the bar with the whole hand, not just with two or three fingers"). However, no specific instructions were given about how to grasp the bar (i.e. overhand or underhand) or which hand should be used to grasp the bar (i.e. left or right). Children were informed that movement accuracy was of utmost importance and that they should perform the task at a comfortable speed (instructions translated from German: "take your time, put the bar into the hole in the cube, but try not to touch the edges of the cube"). Grasp postures were recorded using a video camera (Panasonic NV-DX 100) placed 3 m from the right horizontal plane of the apparatus.

During unimanual trials only one bar was positioned on the support cradles. Children were asked to reach for the bar with either their left or right hand and to place either the black or white end of the bar into the target. Children performed two trials per condition, resulting in a total of 8 trials, comprised of the two 2 start-orientation (black end to the right, black end to the left), 2 end-orientation (black end inserted to the target, white end inserted to the target), with each trial performed twice. The start orientation of the bar was manipulated, such that for half of the trials the black end of the bar was oriented to the right, and for the other half of the trials the black end of the bar was oriented to the left. The start orientation of the bar (black end left, black end right) was counterbalanced across children, and the individual trials were randomized. End-state comfort satisfaction was defined by initial grasps that resulted in thumb up postures at the end of the movement (Fig. 1b). Thus, for final left end-down trials, end-state comfort was defined by the adoption of initial underhand grasp postures. For final right end-down trials, end-state comfort was defined by the adoption of initial overhand grasp postures.

In the bimanual portion of the experiment, two bars were positioned on the supports and the child was asked to reach for the two bars with both hands simultaneously and to place the instructed ends into the two targets. As in a previous study on neurologically healthy adults (Hughes & Seegelke, 2013) we differentiated between four object end orientation conditions: (1) when both objects required overhand grasp postures to satisfy end-state comfort (OO), (2) when end-state was satisfied by the adoption of an overhand grasp posture for the left object and underhand grasp posture for the right object (OU), (3) underhand grasp posture for the left object and overhand grasp posture for the right object (UO), and (4) end-state comfort was satisfied by grasping both objects with underhand grasp postures (UU). Children performed a total of eight trials, comprised of the four object end-orientation conditions (OO, UU, OU, UO), with each trial performed twice. The start orientation of the objects was blocked and counterbalanced across the participants, and the individual conditions were presented in a randomized order.

The primary outcome measure was the proportion of trials that participants complied with end-state comfort (i.e. selected a grasp posture that resulted in comfortable final posture(s) across unimanual and bimanual versions of the bar transport task [i.e. overall end-state comfort]).

*Manual dexterity assessment from the movement assessment battery for children 2*

The developmental status of fundamental movement skills was assessed using the age-class 1 (ages 4–6) manual dexterity assessment from the M-ABC-2 (Henderson & Sugden, 1992; Henderson, Sugden & Barnett, 2007; Petermann, 2009; cf. Jongbloed-Pereboom et al., 2013). The M-ABC-2 is a frequently used standardized motor test to assess movement difficulties in children and is well-known for a high standard of reliability and validity (Henderson & Sugden, 1992). The M-ABC-2 was administered by a trained experimenter according to the procedures outlined in the M-ABC manual. Children were asked to post 12 coins into a money box with the preferred hand and then the other hand (posting coins), to thread 12 beads onto a string (threading beads), and to trace with a pen between two curved lines of 4 mm apart without going over the boundary lines (drawing trail). Performance on each task corresponds to a score range from 0 to 5, with 0 indicating complete success and 5 indicating the severe movement impairment. Scores of 0 are achieved by 75 % of the normative sample, and scores of 5 by the lowest 2 %. Children who test below the 15th percentile on this measure are considered to have some motor impairment, while children who score below the fifth percentile have severe motor impairment (Sugden, 2006). The primary outcome variable was the total score ($z$-scores). All conversions of scores to the standard scores were based on the German norms (Petermann, 2009).

*Animal stroop (AS) task*

The ability to inhibit irrelevant information or pre-potent responses was measured using the animal Stroop task (Stroop, 1935; Wright, Waterman, Prescott & Murdoch-Eaton, 2003). In the computerized version of the animal Stroop task (v3.9; Wright et al., 2003), the children performed three conditions (congruent, control, and incongruent), each consisting of 24 farm animal pictures randomly presented. Four farm animals were used in each condition (i.e. cow, duck, pig, and sheep). In all three conditions, children were instructed to name the body of each animal regardless of the head attached to the animal. In the congruent condition, the head of each animal corresponded to the correct body. In the control condition, human heads were placed on animals' bodies. In the

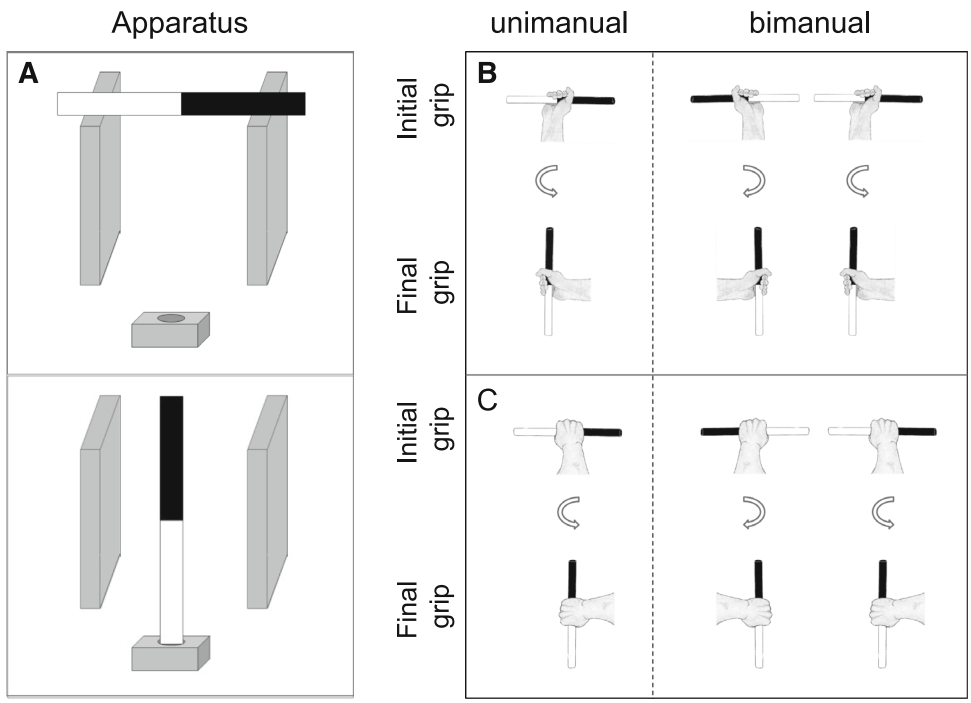


**Fig. 1** Unimanual and bimanual bar transport task. **a** Depiction of the apparatus with the *bar* resting on the supports in the start position (*upper panel*) and being inserted in the target in the final position (*lower panel*). **b** Examples of end-state comfort compliant grasp postures in unimanual and bimanual conditions, when the *white* end has to be inserted into the target. **c** Examples of grasp postures not satisfying end-state comfort in the unimanual and bimanual (*white* end-down) condition

incongruent condition, chimeric animals were shown (e.g., a cow's head attached to a pig's body). Dependent variables included the *differences* in average response time ($RT_{interference}$) and error rates ($Error_{interference}$) between incongruent and control trials. Higher scores in the interference indexes imply a greater difficulty in controlling the prepotent response in the incongruent condition (cf. Wright et al., 2003).

*Corsi block-tapping (CBT) task*

The Psychology Experiment Building Language (PEBL; Mueller, 2013; see Piper et al., 2012 for validation) computerized version of the Corsi Block-Tapping Test (Corsi, 1972; Kessels, van Zandvoort, Postma, Kappelle & de Haan, 2000) was used as a measure of visuospatial working memory capacity. Children were given a standardized set of instructions presented on the screen prior to the test. Once the test began, blue-colored blocks were displayed on a black background, arranged in a static spatial array on the screen. Blocks were illuminated (i.e. changed color from blue to yellow) in a predetermined sequence and children were instructed to reproduce the sequence by clicking on the blocks in the same order they were illuminated. The span of the sequence began with 3 target blocks being illuminated with an inter-stimulus interval of 1000 ms. There was a 1000 ms interval between trials during which participants saw the word "Ready?" (in german) in white text centered on a black background. Two trials of each span-length were administered regardless of accuracy on the first trial. Span lengths ranged from 3 to 9 targets per trial and trials increased by one item as long as the participant correctly reproduced one of the two prior trials. When two trials of a span length were failed, the test was discontinued. The primary outcome variable was $CBT_{memory\ span}$, which was defined as the maximal sequence length that resulted in correct recall in 50 % of trials.

*Tower of London (TOL) task*

The PEBL computerized version of the TOL task was administered to assess response planning and problem solving abilities (Anderson, Anderson & Lajoie, 1996; Shallice, 1982). Children were informed that the aim of the task was to move a pile of disks from their original configuration to the configuration shown at the top of the computer screen. Children were told that they could move only one disk at a time, and that they could not move a disk onto a pile that has no more room. Further, children were instructed to try to solve the task in as few steps as possible. The stimuli were based on the standard set of 12 problems (Shallice, 1982) that consisted of 3 disks and constrained pile heights (1, 2, 3). The percent of trials with perfect solutions ($TOL_{percent\ success}$, i.e. trials solved in the minimum number of moves) was calculated and used as a measure of optimal planning and execution of the task.

## Results

Preliminary analyses were conducted on the executive function measures to check for normality, sphericity (Mauchly test), univariate and multivariate outliers, with no serious violations noted. There were no notable declines (indicative of fatigue or boredom effects) or improvements (indicative of learning effects) in performance across the experiment, indicating that the order effects due to the standardization of task administration were minimal. Data were collapsed across gender and age group, as preliminary data analysis did not reveal any systematic differences in handedness (left-handed, right-handed), gender (boys, girls) or between age groups (5-year-olds, 6-year-olds). To control for problems of multiple significance testing (e.g., false discovery rate) we applied a Benjamini-Hochberg Procedure to the data (Benjamini & Hochberg, 1995). Means and standard deviations for all measures of interest are presented in Table 1. Raw correlations between all study variables are presented in Table 2.

### Anticipatory motor planning and manual dexterity

Correlations between the bar transport task and the M-ABC-2 manual dexterity were non-significant (Table 2), indicating that anticipatory motor planning performance and scores of manual dexterity are not associated with one another.

**Table 1** Descriptive statistics for the measures of interest for the sample of 5- to 6-year-old children ($N = 40$)

| | Mean | SD |
|---|---|---|
| Bar transport task (% ESC compliance) | | |
| Unimanual | 71.56 | 19.61 |
| Bimanual | 59.69 | 24.76 |
| Overall | 63.65 | 20.37 |
| M-ABC-2 (*Z*-score) | | |
| Posting coins | 9.93 | 2.89 |
| Threading beads | 8.80 | 3.07 |
| Drawing trail | 9.50 | 2.71 |
| Total score | 9.70 | 2.60 |
| Animal stroop | | |
| $\mathrm{Error}_{\mathrm{interference}}$ (Δ %) | 3.54 | 17.54 |
| $\mathrm{RT}_{\mathrm{interference}}$ (Δ ms) | 131.83 | 177.89 |
| Corsi block-tapping | | |
| Memory span | 3.16 | 0.80 |
| Tower of London | | |
| Percent success | 45.21 | 16.22 |

**Table 2** Raw correlations among study measures

| | Bar transport: overall | M-ABC-2: total score |
|---|---|---|
| M-ABC-2: total score | 0.101 | – |
| CBT: memory Span | 0.321* | 0.349* |
| TOL: percent success | 0.432** | 0.122 |
| AS: $\mathrm{RT}_{\mathrm{interference}}$ | −0.054 | 0.253 |
| AS: $\mathrm{Error}_{\mathrm{interference}}$ | 0.205 | −0.407** |

Asterisks represent significance level of bivariate Pearson's correlation (*$p < 0.05$, **$p < 0.01$, with Benjamini-Hochberg Procedure applied to control for problems of multiple significance testing)

### Anticipatory motor planning and executive functioning

Overall, children selected initial grasp postures that ensured end-state comfort in 63.7 % of trials during the bar transport task. End-state comfort was higher for unimanual trials (71.6 %) compared to bimanual trials (59.7 %), however despite this numerical difference, a one dimensional Chi square analysis indicated that grasp behavior was similar between unimanual and bimanual planning conditions, $\chi^2_{(1)} = 2.368$, $p = 0.124$. When overall bar transport task performance was analyzed by classifying end-state comfort compliance into one of the four categories (0–20, 21–50, 51–80, and 81–100 %, Hughes et al., 2012; Thibaut & Toussaint, 2010), it was found that 8 children (20 %, 1 left-handed child) complied with end-state comfort in more than 80 % of trials, and thus achieved high scores on the bar transport task. 16 children (40 %, 2 left-handed children) satisfied end-state comfort in 51–79 % of trials, 16 children (40 %) satisfied end-state comfort in 21–50 % of trials. No children obtained very low scores (<20 % end-state comfort).

After correcting for multiple comparisons, overall end-state comfort sensitivity in the bar transport task was found to be positively correlated with $\mathrm{TOL}_{\mathrm{percent\ success}}$ ($r = 0.432$, $p < 0.001$) and $\mathrm{CBT}_{\mathrm{memory\ span}}$ ($r = 0.321$, $p < 0.01$), but not AS measures ($\mathrm{RT}_{\mathrm{interference}}$ $r = -0.054$, $\mathrm{Error}_{\mathrm{interference}}$ $r = 0.205$). Multiple regression analysis was employed to identify the main predictors of anticipatory motor planning, and to study the relative strength of these predictors when controlling for the others. The two executive function measures found to be significantly related to overall end-state comfort sensitivity in the bar transport task ($\mathrm{TOL}_{\mathrm{percent\ success}}$ and $\mathrm{CBT}_{\mathrm{memory\ span}}$) were entered into the regression analysis as potential predictors. Analysis revealed that anticipatory motor planning was significantly predicted by the full model (adjusted $R^2 = 0.174$, $F(2,37) = 5.11$, $p < 0.01$), with $\mathrm{TOL}_{\mathrm{percent\ success}}$ explaining 13.2 % of grasp posture planning variance ($\beta = 0.363$, $t(37) = 2.31$, $p < 0.05$).

### Manual dexterity and executive functioning

The mean total score of the manual dexterity assessment from the M-ABC-2 was 9.7 (SD 2.6) with individual results varying from 3 to 15. Regarding individual test results, 33 children (82.5 %) showed normal motor function (with five children scoring above the 5th centile), five children (12.5 %) were borderline function (>5 to ≤15 centile), and two children (5 %) obtained a total motor impairment score at a clinical level at or below the 5th centile for which motor intervention is recommended (Henderson & Sugden, 1992).

After correcting for multiple comparisons, analysis indicated that total M-ABC-2 scores were negatively correlated with AS $Error_{interference}$ ($r = -0.407$, $p < 0.01$), and positively correlated with $CBT_{memory\ span}$ ($r = 0.349$, $p < 0.01$). The two executive function measures found to be significantly related to M-ABC-2 total score (AS $Error_{interference}$ and $CBT_{memory\ span}$) were entered into the regression analysis as potential predictors of manual dexterity performance. Regression analysis revealed that manual dexterity was significantly predicted by the full model (adjusted $R^2 = 0.226$, $F(2, 37) = 6.70$, $p < 0.01$), with AS $Error_{interference}$ ($\beta = -0.381$, $t(37) = -2.70$, $p < 0.05$) and $CBT_{memory\ span}$ ($\beta = 0.318$, $t(37) = 2.25$, $p < 0.05$) explaining 14.5 % and 10.1 % of the variance in M-ABC-2 total score after controlling for the other predictor variable, respectively.

## Discussion

The current study examined the extent to which measures of cognitive functioning correlate with anticipatory motor planning and manual dexterity performance in a group of normally developing 5- to 6-year-old children. Overall, anticipatory motor planning performance in our sample of 5- to 6-year-old children was, as can be expected, worse than in neurologically healthy adults (Hughes & Seegelke, 2013; Rosenbaum et al., 1990; Weigelt et al., 2006). However, results are compatible with prior studies in adult populations demonstrating higher end-state comfort compliance for unimanual compared to bimanual conditions (Hughes & Franz, 2008; Hughes, Haddad, Franz, Zelaznik & Ryu, 2011), indicating that greater cognitive resources are required to plan bimanual movements (Hughes & Franz, 2008; Logan & Fischman, 2011).

In line with our original hypotheses, results of the current study indicated that anticipatory motor planning and manual dexterity were not associated with one another (Jongbloed-Pereboom et al., 2013). This finding is supported by the regression analyses revealing that response planning was a significant predictor of anticipatory motor planning performance, whereas inhibitory control and working memory capacity were significant predictors of manual dexterity scores. Taken together, these results demonstrate that these two motor skill performance measures differ from one another, not only due to their physical demands, but also because of the cognitive processes that are required for successful task performance.

Motor skill performance is a broad term consisting of a variety of distinct abilities. We argue that the two motor skills aspects measured in the present study required different motor and cognitive abilities. It is our opinion that the tasks included in the M-ABC-2 (i.e. coin posting, bead threading, and drawing trail) required coordinated movements of the fingers or wrists when manipulating the object/s of interest, and as such more appropriately measured aspects related to fine motor execution. In contrast, the bar transport task required a lower degree of fine motor control during object manipulation, but placed greater demands on motor planning processes that occurred prior to movement initiation (than the M-ABC-2 manual dexterity sub-tasks). Taken together, the results argue against the notion of a single general motor ability, and indicate that manual dexterity and anticipatory motor planning involve different specialized skills (e.g., inhibitory control and working memory capacity vs. problem solving and decision-making abilities).

Results indicated that anticipatory motor planning performance was positively correlated with response planning and working memory capacity, with regression analysis revealing that response planning performance was a significant predictor of grasp posture planning performance. Successful motor planning requires that individuals are able to formulate a plan based on future task demands, to monitor the task as it unfolds, and to update the plan in response to changes in the environment. Likewise, the Tower of London task requires planning and sustained cognitive control of behavior towards a goal. A mental representation of the path from the start state to the goal state must be formed, and requires that the multiple intermediate steps be organized as sub-goal operations. Moreover, as each sub-goal operation is mentally executed, the problem state representation must be amended and alternative operations evaluated. This process must be repeated until the goal state is reached and the selected sequence of operations can be physically executed. The results of this study, therefore, indicate that grasp posture planning abilities in 5- to 6-year-old children are specifically associated with visuo-spatial search ahead abilities (Berg & Byrd, 2002) and the sustained cognitive control of behavior towards a goal.

Although $CBT_{memory\ span}$ scores did not contribute unique variance to the full regression model, results indicated that anticipatory motor planning performance was positively correlated with working memory capacity, such that children with higher end-state comfort scores had higher working memory scores than children that did not select initial grasp postures that complied with end-state comfort. This finding is consistent with previous work in children (Stöckel et al., 2012) and adults (Logan & Fischman, 2011; Weigelt et al., 2009), indicating that the ability to plan an action, and to maintain that action plan throughout the execution of the task, is influenced by one's working memory ability.

The present study also revealed that manual dexterity scores were correlated with inhibitory control and working memory capacity, with regression analysis indicating that inhibitory control and working memory capacity accounting for 14.5 and 10.1 % of the variance in manual dexterity scores. The negative correlation between manual dexterity scores and Stroop task performance (inhibitory control) indicates that children with poor motor coordination skills had greater difficulty inhibiting irrelevant information, whereas children with good motor coordination skills were able to inhibit pre-potent responses in order to successfully complete the task goal. This finding is compatible with previous investigations into normally developing (Livesey et al., 2006) and motor-impaired children aged between 5 and 7 years (Michel et al., 2011). These studies have reported that children with poor motor coordination skills are less able to selectively attend to specific stimuli and inhibit pre-potent responses than their more motorically skilled classmates. For example, Michel et al. (2011) utilized a longitudinal research design to examine motor coordination and executive functions in children with and without motor coordination impairments. The authors reported that motor-impaired children had lower inhibition dominant responses in the Stroop test compared to children without motor impairments, and that these deficits persisted over the 1-year testing period.

Contrary to our original hypothesis, results revealed that working memory capacity was positively correlated with manual dexterity scores, and independently accounted for 10.1 % of the variance in manual dexterity scores. Although this finding is incongruent with existing studies in normally developing children that have reported similar working memory scores regardless of manual dexterity performance (Pangelinanet al., 2011; Roebers & Kauer, 2009), our results are consistent with findings demonstrating that children with DCD (Piek et al., 2007) and ADHD (Pennington & Ozonoff, 1996) score significantly lower on tests of working memory capacity than normally developing children. Successful manual dexterity performance requires an individual to be able to select the correct motor response, hold a mental representation of the task throughout its execution, detect and correct errors, and update motor commands based on online feedback. As such, it seems likely that successful manual dexterity performance would depend, at least partly, on working memory capacity. Research has established that working memory is composed of separable interacting components, and that different working memory systems are involved in spatial and in verbal tasks (for a review see Baddeley, 2003). It is possible that the discrepancy between our results and those of previous studies (Pangelinan et al., 2011; Roebers & Kauer, 2009) arise from methodological issues related to the measures used to assess working memory. The Corsi Block-Tapping Test used in the present study is a measure of visuospatial working memory capacity, whereas the tests used in prior studies measured short-term spatial memory (Backwards color recall test [Roebers & Kauer, 2009], Spatial working memory assessed by the Cambridge Neuropsychological Test Automated Battery [Pangelinan et al., 2011]). As such, future research should use multiple measures when examining relations between processes of interest, as this will allow researchers to examine whether the results of different measures converge on a single result and reduce the problem that the correlations may be due to unrelated variance.

## Limitations and practical implications

This study includes several limitations. First, the current study does not address causality or underlying mechanisms, nor does it consider a possible reciprocal association between motor coordination and executive functioning. Second, we did not assess other executive functions (e.g., attention, cognitive flexibility) that may be important for motor skill proficiency. It would also be useful to manipulate the constraints within a given task (i.e. number of action steps, required degree of object rotation, hand used to manipulate the object) or have children perform multiple anticipatory motor planning tasks (i.e. bar transport task, overturned glass task, handle rotation task), as it is likely that children would need to engage different executive functions in order to select an appropriate grasp posture. Given the rapid change in both executive functions and motor skill proficiency during the preschool and primary school years, the next step in this line of work would be to investigate the long-term development of cognitive and motor skills using a longitudinal design, and include different and more comprehensive assessments of motor skills (i.e. using everyday objects embedded with miniaturized sensor technology that allows for the analysis of kinematic and grip force, e.g., Campolo, Laschi, Keller & Guglielmelli, 2007), executive functions, and academic performance (e.g., reading and mathematics). Last, although power analysis indicated that a sample size of 36 children would be sufficient to detect a moderate effect with a power of 0.80 and an alpha of 0.05 (parameters were chosen so as to match those in Livesey et al., 2006), the modest sample size ($n = 40$) of the present study may have played a role in limiting the significance of some of the statistical analyses conducted. Indeed, it is clear that small sample sizes decrease statistical power, which negatively affects the ability of detecting a true effect, and result in a larger variance of the estimates of the parameter being estimated (Cohen, 1988).

Limitations notwithstanding, we believe that this study offers valuable empirical evidence regarding the relation between cognitive functioning and motor skill performance in normally developing 5- to 6-year-old children. First and foremost, we found that anticipatory motor planning and manual dexterity performance were not associated with one another, indicating that these abilities capture different aspects of human performance. When considering the motor skill components separately, response planning and working memory performance were found to correlate with anticipatory motor planning, with response planning significantly predicting anticipatory motor planning performance. We also observed significant correlations between manual dexterity performance and inhibitory control and working memory performance, with both executive function measures significantly predicting manual dexterity performance.

Based on the results of this study we argue that motor skills should be treated as specific, as they do not draw on exactly the same executive function components. As such, practitioners who wish to develop training and intervention programs to help young children develop and improve cognitive-motor skills should consider the cognitive and motor abilities of each individual child. Training and intervention programs should target children as young as 4 or 5 years of age, so as to offset future cognitive and motor deficits (Diamond, Barnett, Thomas & Munro, 2007), and should also capitalize on the relations observed in the present study. Specifically, working memory training is likely to help improve deficits in both anticipatory motor planning and manual dexterity. Additionally, problem-solving training is likely to improve anticipatory motor planning performance, and manual dexterity would benefit from inhibition training. That said, given that we did not address causality between aspects of cognitive and motor performance in the present study, improvements in cognitive functions are also possible to occur from training of related motor skills.

In addition to activities and programs that specifically target executive functioning (e.g., computer-based working memory and reasoning training), improvements are also likely to occur if training programs contain a motor, as well as a cognitive, component (Manjunath & Telles, 2001). For example, Manjunath and Telles (2001) randomly assigned twenty 10- to 13-year-old girls to either yoga or physical training for 75 min a day, 7 days a week for 1 month. They found that girls who did yoga had greater performance gains in the TOL task, especially when task conditions were more difficult and complex, than did girls in the control group. Future research should investigate the interrelations between cognitive and motor skills from childhood to early adulthood, and include more comprehensive assessments of motor skills and executive functions. In addition, it would be useful to examine how cognitive-motor abilities predict academic performance (e.g., arithmetic, reading, and writing competencies) in later childhood.

**Ethical standard** The authors declare that they have no conflict of interest. All procedures performed in this study were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from parents or guardians of all children included in this study.

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