THE RELATIONSHIP BETWEEN EXECUTIVE FUNCTION AND FINE MOTOR SKILLS IN 2-YEAR-OLD CHILDREN

by

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This thesis is dedicated to all my mentors over the years. I am truly thankful for you all.

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ABSTRACT

Cognitive and motor processes are tightly interwoven during development (Diamond, 2000). More specifically, numerous studies point to a link between fine motor skills and executive functioning (EF) in 3- to 6-year-olds (e.g., Oberer et al., 2017; MacDonald et al., 2016); however, it is unclear if this relation exists at younger ages. For example, Gottwald et al. (2016) found that 18-month-old's fine motor skills and EF were not related; whereas, Wu et al. (2017) found that fine motor skills at 2-years predicted EF at 3-years. Therefore, the current project aimed to further explore EF and fine motor skills in typically developing 2-year-olds. Forty-three 2-year-olds (m = 31.00 mo; 15 girls; range = 25-35 mo) participated. Participants completed the Minnesota Executive Function Scale (MEFS), Spin the Pots, Shape Stroop, Snack Delay, and the Fine Motor portion (FMQ) of the Peabody Developmental Motor Scale Version-2. The FMQ has two subtests: Grasping (whole-hand and finger grasping) and Visual Motor Integration (VMI; eye-hand coordination). MEFS and FMQ were not positively correlated before or after controlling for age (in mos) and verbal IQ. For the fine motor subtests, MEFS positively correlated with VMI only after controlling for age and verbal IQ ($r = 0.57$, $p < 0.01$), but not Grasping ($r = -0.07$, $p > 0.10$). Regression analysis controlling for age and verbal IQ showed that VMI significantly predicted MEFS performance (adj R^2 = 0.32, $\beta = 0.51$, $p < 0.01$), but not Grasping (adj R^2 = 0.10, $\beta = 0.13$, $p > 0.10$). No other EF measures produced significant results. These findings demonstrate a link between general EF and visual-motor integration in 2-year-olds. Future research should assess what influence fine motor skill training, specifically VMI skills, has on EF development in young children.

CHAPTER 1: INTRODUCTION

Our executive functioning (EF) skills have the important role of controlling and overseeing our self-regulation and goal-directed behaviors. Strong EF skills are imperative for success throughout development and into adulthood, which has led to a great deal of research using the construct. For example, higher EF skills correlate with better performance on assessments of general knowledge, math, reading comprehension, and vocabulary in early childhood (Allan, Hume, Allan, Farrington, & Lonigan, 2014; Jacob & Parkinson, 2015). In addition, EF skills at 2-year of age predict body mass index and body image/eating concerns at ten, with higher EF related to lower body mass index and less body image/eating concerns (Graziano, Kelleher, Calkins, Keane, & Brien, 2013). Furthermore, individuals scoring lower on measures of EF in childhood are more likely to be convicted of crimes, make poor financial decisions, and develop poor health, (Moffitt, Arseneault, Belsky, Dickson, Hancox, Harrington, ... & Sears, 2011). Overall, EF skills in children and adults predict factors of academic success, health and wellness, and social and societal success.

EF is comprised of three distinct components: working memory, inhibitory control, and cognitive flexibility (e.g., Zelazo, Blair, & Willoughby, 2016; Miyake & Friedman, 2012; Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000; Garon, Bryson, & Smith, 2008). Working memory is an individual's ability to store and refer to previously learned information while manipulating or using information in some way at the same time, such as in remembering and using directions. One commonly used task to measure working memory in young children is spin the pots (Hughes & Ensor, 2005). In this task, children find stickers hidden in boxes under a scarf, and the boxes change position between trials. The task challenges working memory by requiring the child to hold in mind the boxes without stickers, based on the box's appearance, while investigating the tray for other boxes that still have stickers inside.

Deliberate suppression of attention to objects, previously learned rules, and other stimuli in favor of attention directed to stimuli that are more appropriate defines inhibitory control. Inhibitory control tasks generally fall into one of two categories: conflict inhibition and delay inhibition. One commonly used delay inhibition task used with young children is the gift delay task (Kochanska, Murray, & Harlan, 2000). In this task, children must refrain from turning around and looking while the experimenter noisily wraps a present behind the child's back. The longer the child refrains from turning to look, the better inhibitory control the child displays. One commonly used conflict inhibition task is the day/night Stroop task (Gerstadt, Hong, & Diamond, 1994). This is an adapted version of the classic Stroop Task. Children are instructed to say “night” when presented with card displaying a sun and “day” when presented with a card displaying the moon. Higher proportion of responses that oppose, or conflict, the stimulus, the better the child is able to inhibit the incorrect response.

Cognitive flexibility is defined as the ability to maintain focus and flexibly shift attention to changing environments and stimuli. Planning, problem solving, and the ability to see the world from multiple perspectives are all examples of cognitive flexibility. A child’s willingness to change plans without becoming frustrated exhibits strong cognitive flexibility (e.g., Zelazo et al., 2016). One commonly used cognitive flexibility task is the dimensional change card sort (DCCS) task. The DCCS presents children with cards, each having differently colored shapes. The task is administered with a pre-switch and post-switch condition. In the pre-switch, the child sorts cards based on the color of the shape. In the post-switch condition, the child sorts the cards based on the shape, while disregarding the color (Zelazo, Frye, & Rapus, 1996). The task measures the child’s ability to flexibly switch between given task conditions.

In a review of the literature, Garon et al. (2008) concluded working memory skills are the first EFs to emerge in development, followed closely by inhibitory control skills. She also claims cognitive flexibility is dependent on the prior development of both working memory and inhibitory control, and therefore cognitive flexibility is the final executive function skill to emerge in the developing child. In 2-year-olds, working memory and inhibitory control are present and developing, while cognitive flexibility is just emerging as a unique cognitive processes. These three components rapidly develop into complex, cognitive functions between ages 3 and 5 (Garon et al., 2008). Due to the importance of EF skills throughout the lifespan, there has been a wealth of research investigating how EF skills relate to other skills.

One area has been investigating the relationship between EF and motor skills. Originally hypothesized as separately developing constructs, cognitive (PFC) and motor (cerebellum) regions of the brain not only develop together but they are interrelated throughout development and into adulthood (Diamond, 2000). For example, brain-imaging studies have shown that while performing cognitive tasks, the PFC and the cerebellum experience increased activity and individuals with cerebellar damage exhibit deficits in an array of cognitive tasks (Diamond, 2000). Diamond's ideas have developed into an ever-expanding field captivated by the neural circuitry behind the relationship between the PFC and the cerebellum. One line of research has looked into higher-order cognitive functions carried out by the PFC, EF, and their relationship to motor skills in development. Understanding this relationship is not only interesting given the neural links between brain regions, but also important given the impact motor skills and cognition have on a variety of other developmental trajectories. A recent review by McClelland & Cameron (2019), also discusses the importance of EF and motor skills developing together and playing an important role in children's early academic lives.

How might cognitive ability and motor ability be related? One theory follows the Embodied Cognition Approach of development (e.g., Gibson, 1988; Smith & Gasser, 2005; Thelen, 1995; Thelen, 2000). According to this theory of motor development, emerging motor skills lead to more enriched ways and opportunities to interact with the environment. For example, reaching can develop from a variety of environments. Infants need to increase their spontaneous movements to achieve their desired goal, likely an enticing toy or food, likely both having the same destination. Infants solve this reaching problem by reducing uncontrolled actions in favor of directed reaches. The more infants converge on movement patterns that result in successful actions, the more infants are able to learn about their environment. One way this idea has been demonstrated in the literature is by providing infants with early experiences with motor movements, such as reaching, that they would not normally have. For example, in pre-reaching infants, wearing Velcro lined gloves, "sticky mittens", for ten minutes each day during a two-week period while playing with toys covered in Velcro increased the number and quality of object interactions over controls (Needham, Barrett, & Peterman, 2002). When given the opportunities, children will learn and develop through their interactions with objects, people, or even the environment itself. These increasingly complex interactions promote the development of other skills, such as cognitive abilities and social abilities (e.g., Campos, Anderson, Barbu-Roth, Hubbard, Hertenstein, & Witherington, 2000; Piaget & Cook, 1954).

Given this approach that motor skills lead to the development of cognitive skills, we were interested in exploring if fine motor skills in young children were related to their EF skills. Fine motor skills are motor skills performed using our small muscle groups, primarily located in our hands. For example, a fine motor task might involve drawing, stringing beads onto a string, or building a tower out of blocks. Successful completion of these tasks requires the development of the precise fine motor control. In typically developing children, precision fine motor tasks can stratify children's current and future fine motor skill. Chen and colleagues (2010) demonstrated this in 18-21 month old children recording kinematic data while building block towers. Children were split into groups, high and low, based on the height of tower they were able to construct. Those in the high tower group reached peak velocity earlier in their reach, followed by elongated deceleration and adjustment phases. These longer deceleration and adjustment phases are indicative of mature, adult-like reaching. When the children returned for a second testing phase one year later, the low-tower group was able to build the same size tower as the high-tower group. However, group differences in kinematics persisted. Children in the high-tower group placed the blocks faster on their tower when completing the precision tower building, indicating the transfer of their previously advanced reaching characteristics (Chen, Keen, Rosander, & Von Hofsten, 2010). Overall, these results provide evidence that in the typically developing population, tasks requiring precise control are able to distinguish levels of fine motor maturity, and these individual differences in performance persist in children up to 3-years-old. We propose these individual differences in fine motor skills seen in young children also relate to individual differences in other skills, such as EF.

A significant relationship exists between various measures of each EF construct and fine motor skills in children (Becker, Miao, Duncan, & McClelland, 2014; Cameron, Brock, Murrah, Bell, Worzalla, Grissmer, & Morrison, 2012; Claxton, King, Leung, & Carlson, in prep; Houwen, van der Veer, Visser, & Cantell, 2017; Livesey, Keen, Rouse, & White, 2006; MacDonald, Lipscomb, McClelland, Duncan, Becker, Anderson, & Kile, 2016; Oberer, Gashaj, & Roebers, 2017; Rigoli, Piek, Kane, & Oosterlaan, 2012b; Roebers & Kauer, 2009; Roebers, Röthlisberger, Neuenschwander, Cimeli, Michel, & Jäger, 2014; Stöckel & Hughes, 2016; Wu, Liang, Lu, & Wang, 2017). With increasing age, the relationship between cognition and fine motor skill seems to dissipate after puberty, as younger children consistently show the most robust relationships between the two measures (van der Fels, te Wierike, Hartman, Elferink-Gemser, Smith, & Visscher, 2015).

Whereas fine motor skills and EF are positively correlated starting at 3-years of age (e.g., Oberer et al., 2017; MacDonald et al., 2016), it is unclear as to whether this link exists at earlier ages. To our knowledge, only two studies have examined this link between fine motor skills and EF in children younger than 3-years of age (Wu et al., 2017; Gottwald, Achermann, Marciszko, Lindskog, & Gredebäck, 2016). Wu and colleagues (2017) assessed general cognitive and motor abilities at 1-year of age and again at 2-years of age using a standardized observational measurement, the Bayley Scales of Infant and Toddler Development. They assessed EF through two working memory and two delay inhibition tasks at 3-years of age. They found that EF at 3-years of age was unrelated to fine motor skills at 1-year of age. However, fine motor skill at 2-years of age was related to EF at 3-years of age (Wu et al., 2017). The authors only assessed EF at 3-years of age. It is unclear if this relation between fine motor skill and EF exists in 2-year-olds.

In the other study, Gottwald and colleagues (2016) measured both EF and fine motor skills at 18-months of age. To assess EF, they used 3 age-appropriate tasks measuring working memory and inhibitory control. To assess motor skills, they used a prospective motor control reaching task, which measured the infant's ability to plan their motor measures in advance. In addition, they had parents complete the Vineland Scales of Adaptive Behavior, a standardized parent-report measure of their infant's fine and gross motor skills. Interestingly, they found that neither the fine nor the gross motor skills of the 18-month-old infants, as assessed through the parent-reported motor skill questionnaire were related to their EF skills. However, the prospective motor control measure, which assessed the ability of the infants' to plan their motor measures in advance, was significantly correlated with working memory and inhibition. Therefore, those infants who were better at planning their motor actions in advance also performed better on the EF tasks. Gottwald and colleagues argued that early in development, planning motor actions and EF develop from the same common ability (Gottwald et al., 2016). It is also possible motor skills and EF develop from the same common ability, however these relationships may not present until later ages.

It remains unclear when this relationship between EF and fine motor skill first emerges. However, given the previous findings of Wu and colleagues (2017) and Gottwald and colleagues (2016), this relationship likely occurs at some point between 18-months and 3-years of age. Therefore, our main question of interest was to ascertain whether fine motor skills are related to EF in typically developing 2-year-old children. To assess fine motor skills we used an experimenter administered standardized measure of fine motor skills (the Peabody Developmental Motor Scales Version-2; Folio & Fewell, 2000; PDMS), which is comprised of a grasping subtest and a visual-motor integration subtest. To assess EF, we used four age-appropriate tasks assessing all three components of EF: working memory, inhibitory control, and cognitive flexibility. Parents also completed the Early Childhood Behavior Questionnaire (Putnam & Rothbart, 2006; ECBQ) in order to provide us with a naturalistic view of the child's self-regulation outside of the research setting. The ECBQ is a parent reported measure of eighteen dimensions of temperament. For the current study, we only used the most relevant dimension to our study: the inhibitory control dimension. Lastly, we had parents complete the MacArthur Bates Communicative Inventory (Fenson, Bates, Dale, Marchman, Reznick, and Thal, 2007; CDI) to provide us with a list of words that children could produce to serve as a measure of verbal IQ.

Based on the previous research, we hypothesized that fine motor skill in both subtests of the PDMS would be positively correlated with the EF tasks, controlling for age and verbal IQ at 2-years of age. We predicted that the relationship between EF and fine motor would be stronger in the working memory and inhibitory control tasks, given working memory and inhibition are more developed than cognitive flexibility in 2-year-olds (Garon et al., 2008).

CHAPTER 2: METHODS

Participants

From our sample of 43 2-year-olds, four were removed. One child did not understand English; one child had a language delay; and two children did not complete at least one executive function task and one fine motor measure. Our remaining group consisted of 39 2-year-olds (15 girls, mean age: 31-months, range: 25- to 35-months). Our sample was comprised of individuals with a high socio-economic status, with 77% of mothers and 81% of fathers holding at least a Bachelor's degree. We recruited families through birth announcements in the local paper matched to public directories, speaking to families at farmer's markets in the Lafayette/West Lafayette area, flyers posted at daycares, and recruitment packets distributed at 2 local daycares where testing also occurred. These families received a recruitment letter in the mail and a follow-up phone call to schedule interested participants. Testing occurred in Lambert Fieldhouse at Purdue University, West Lafayette campus, and at the Ben and Maxine Miller Child Development Laboratory School (MCDLS) and the Purdue University Early Care and Educational Center (ECEC). Two children from the MCDLS and one child from ECEC participated. Children received a small toy (value of approximately $5) for participating and parents received $5 for completing the surveys. The Purdue University Institutional Review Board approved all procedures.

Measures

Executive Function Measures

Minnesota Executive Function Scale (Carlson & Zelazo, 2014; MEFS). The MEFS is a comprehensive, direct measure of EF. The MEFS is an app, validated for children ranging from two years of age to thirteen years of age. Over eight thousand children from age two to thirteen provide the normative base for the MEFS. The scale takes approximately three to six minutes to administer. The scale has seven distinct levels, split into two parts, A and B. For each level, part A explains a rule for the child to complete followed by a rule switch in part B. During the rule switch, the cards have an inverted meaning. For example, in part A of level two, the child matched big and little elephant cards to boxes with the corresponding picture. However, in part B, the child matched the cards with big elephants to the box with the little elephants and the little elephant cards with the big elephant box. Each part has five cards to sort, ten cards to sort per level. To pass any part, the child must correctly sort at least four of the five cards. If the child fails on the first part administered, the app automatically reverts to the previous level until a basal level (one completed sublevel) is obtained. For our sample, all children start on level 1, part A and progress forward. Any failure in our sample ends the task. The app immediately uploads performance to the Reflection Sciences website. The MEFS is a comprehensive measure of EF as all three components are taxed throughout the assessment. Children utilize working memory to hold the rule in mind and use the current rule state to sort the given card. Children must inhibit the desire to sort the current card based on the picture only, instead following the current rule state. Flexibly shifting from one rule to the next challenges the child's cognitive flexibility. The MEFS outcome variables were the number of cards correctly sorted by the child. Higher numbers of correctly sorted cards equates to better performance (Carlson & Zelazo, 2014). One child refused to complete the MEFS.

Spin the Pots (adapted from Hughes & Ensor, 2005; see Figure 1, Figure 2, and Figure 3). Spin the Pots is an EF task, focused on a child's working memory. The experimenter presented a circular tray of brightly colored, visually distinct boxes. The child's age dictated the number of boxes presented (seven boxes for 2-year-olds, Figure 1 and eight boxes for 2.5-year-olds, Figure 2). At the start of the task, the child helped the experimenter place one sticker into each box, with the exception of two boxes, which remained empty. The same two boxes were empty for every child, regardless of age. For each trial, the experimenter covered the boxes with a scarf (Figure 3), and then spun the circular tray 180 degrees. After each spin, the child selected a box and removed the sticker if found. The experimenter gave positive feedback on all successful trials. If the child did not find a sticker, the experimenter replaced the top of the box and spun the tray to begin the next trial ("Uh-oh, that's okay; let's try to find another sticker next time."). The child only chose one box per trial. After all trials were completed, the child found any remaining stickers by opening all the boxes. The number of attempts given to find the stickers is twice the amount of hidden stickers: ten searches for 2-year-olds and twelve searches for 2.5-year-olds. For example, 2.5-year-olds searched eight boxes for a maximum of twelve trials; two of the eight boxes were empty, and the remaining six boxes contained a sticker.

Holding in mind the location of the boxes without stickers and using the empty boxes to guide their search for a box with a sticker requires working memory skills to be successful. The outcome variable was the reverse error score, or the number of searches without finding a sticker subtracted from the total number of trials the child completed. Reverse error scoring compensates for the difference in the number of stickers and boxes presented.

Figure 1: Spin the Pots for Children 24 Months to 29 Months Old

Figure 2: Spin the Pots for Children 30 Months to 35 Months Old

Figure 3: Spin the Pots While the Tray is Spinning

Shape Stroop (Kochanska et al. 2000; see Figure 4 & Figure 5). The Shape Stroop is an EF task, focused on the child's cognitive inhibitory control. The experimenter presented a board with six fruit pasted on it, three large fruit and three corresponding smaller versions of the same fruit. The large fruit were about three times the size of the small fruit. In the rule check, the experimenter named each fruit, and instructed the child to point to the correct fruit ("Show me the big banana."). The experimenter gave positive feedback for correct responses and corrected inaccurate responses. Next, the experimenter flipped the board for the test trials. During the test trials, children were shown the same images however, each small fruit was embedded within one of the other large fruit. The child was asked to point to each of the small fruit ("Show me the little apple."), while inhibiting the urge to point to the large fruit. During the test trials, the experimenter live-coded correct responses, incorrect responses, and self-corrections. Correct responses earned 1 point, self-corrections earned 0.5 points, and incorrect responses earned 0 points. The maximum performance was 3 points. For four children, they did not receive the Shape Stroop test during the administration of the tests.

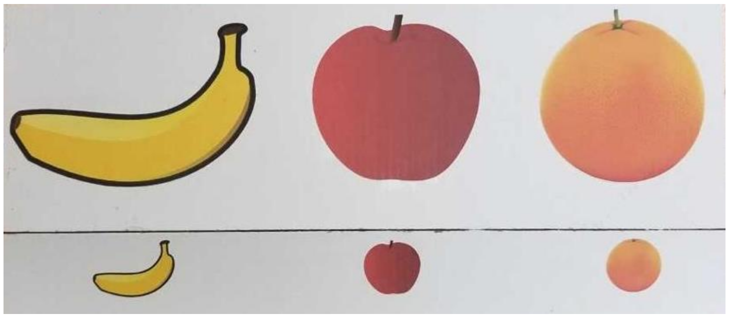

Figure 4: Shape Stroop Rule Check

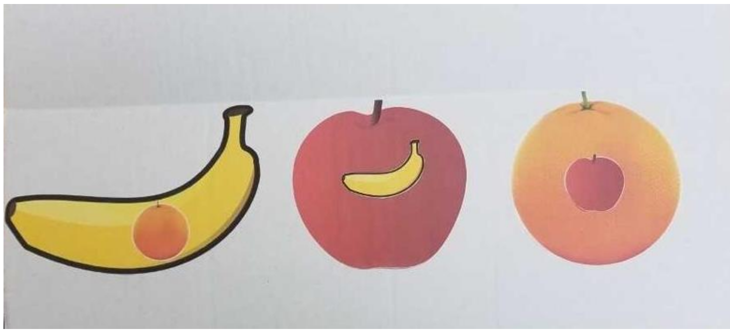

Figure 5: Shape Stroop Test Trials

Snack Delay (Carlson, 2005). The Snack Delay assessed the child's EF, specifically delayed inhibitory control. The child placed their hands on a mat, then the experimenter placed a snack twenty-five centimeters in front of the child under a clear, transparent cup. The parent chose between raisins, goldfish, or a snack supplied by the parent for their child. The experimenter explained the child should wait until after a bell rings before retrieving the snack. After two rule check trials, the child completed four test trials with delays between the presentation of the snack and the ring of the bell. The delay increased from 5, 10, 15, to 20 seconds, respectively, over the four trials. Children were reminded of the rule before every trial ("Remember, wait to get the snack until I ring the bell."). The experimenter did not make eye contact with the child during the delay, to avoid socially influencing the child's behavior. If the child did not touch the cup, they earned 1 point per trial. If they touched the cup, but not the snack they earned 0.5 points. If the child touched the snack, they earned 0 points. Four children did not complete the snack delay, because they did not receive the snack delay test during administration of the tasks. One child did not want to complete the task. For two additional children, their data could not be used due to parental interference.

Early Childhood Behavior Questionnaire -- Short Form (Putnam & Rothbart, 2006; ECBQ). The ECBQ- short form is a parent-reported measure of temperament. The ECBQ measures eighteen different dimensions of toddlers' reactivity and self-regulation abilities in a wide variety of naturalistic settings, including inhibitory control. Some items in each dimension require reverse scoring (subtracting the reported score from seven) before finding the mean of each dimension. Any item left blank or marked as "does not apply" are not included in the mean calculation. Parental-reported measures of inhibitory control relate to laboratory-based tasks of inhibitory control behaviors in young children (Carlson & Moses, 2001; Morasch & Bell, 2011). For the purposes of this study, only the inhibitory control sub-set of this measure was used. This sub-measure was comprised of 6 items. Ten families did not complete the ECBQ.

Verbal Intelligence Measure

MacArthur-Bates Communicative Developmental Inventories (Fenson, et al., 2007; CDI). The CDI assessed the words a child is currently able to say. Children are able to understand many more words than they can use, however, when assessing the child's vocabulary, the parent only selects the words the child says. The parent selected words even if the child had another way of using the word, such as "sketti" for "spaghetti". The CDI Words and Sentences and CDI III forms assessed the child's verbal intelligence. For children up to 30 months, the short form of the vocabulary checklist consisting of 100 words out of the 680 words from the CDI Words and Sentences form was included for analysis. For children above 30 months, the 100-word CDI III vocabulary checklist was used. Raw scores were calculated in each vocabulary section; higher scores correspond to higher verbal intelligence. Five families did not complete the CDI.

Fine Motor Control Measures

Peabody Developmental Motor Scale - 2nd Edition (PDMS; see Figure 6 & Figure 7; Folio & Fewell, 2000). The experimenter assessed the child's fine motor skills with the PDMS.

The PDMS is a standardized motor scale for children birth to seventy-two months old. In the PDMS, there are two fine motor skill subtests, grasping and visual-motor integration. On each subtest, the child began at an entry point which 75% of children in the normative sample at that age were able to pass. Examples of the grasping subtest (Figure 6) included assessing how the child grasped a marker while drawing, how the child grasped multiple blocks with one hand, and proficiency in buttoning and unbuttoning buttons. In the visual-motor integration subtest (Figure 7), children performed tasks like copying shapes on paper, folding paper, stacking blocks into various shapes or objects, and lacing string through beads.

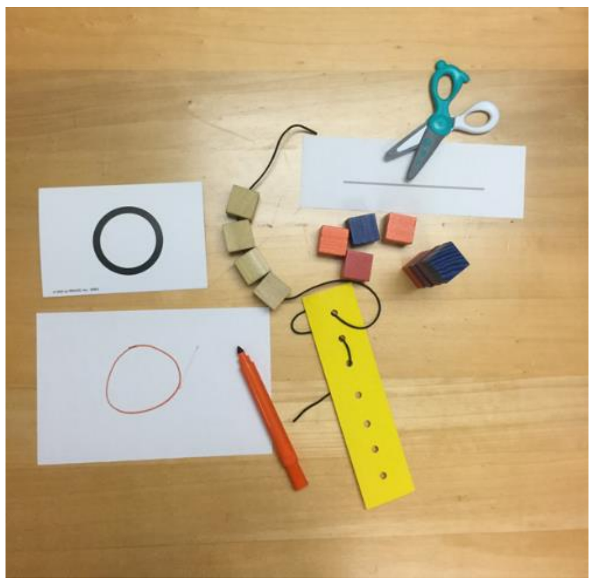

Figure 6: Grasping Materials

Examples of the materials used for the grasping subtest.

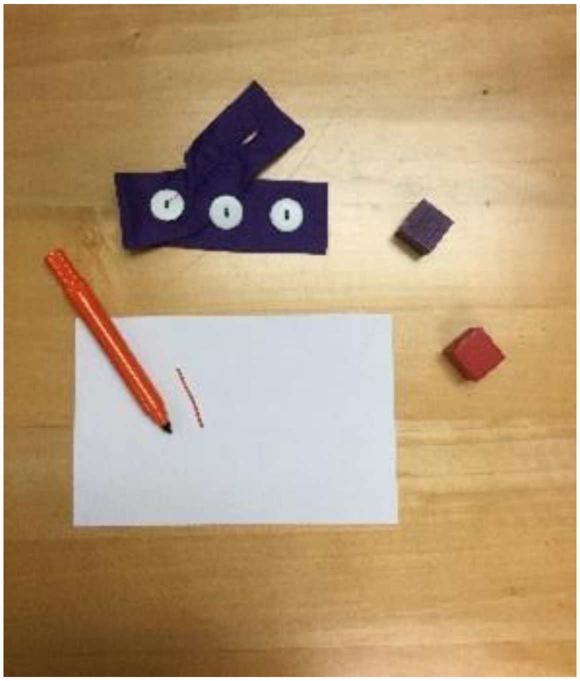

Figure 7: VMI Materials

Examples of the materials used for the visual motor integration subtest.

The child completed each task and the experimenter gave a score of zero, one, or two, with two representing mastery of the task. For each task, the experimenter gave children a maximum of three trials unless the child mastered the task on a previous trial. The subtest continued until the experimenter recorded a basal and ceiling for each child. Mastery of the first three consecutive tasks defined the basal, and the child finished the subtest at their ceiling, or scoring zero (inability to complete the task) on three consecutive tasks. If a child became frustrated or unwilling to complete any of the tasks, the experimenter recorded the number of completed trials, and the experimenter moved on to another task, and the experimenter returned to the uncompleted trials later in the subtest until each task was mastered or administered three times. The experimenter summed all items up to the ceiling. This represents a raw subtest score. The experimenter compared the raw subtest scores across subjects. All of the children completed the grasping portion of the scale. One child did not complete the visual-motor integration portion of the scale.

Procedure

Before completing any tasks, the child was given time to acclimate to the testing environment. While in the motor development lab, parents sat behind the child and completed the questionnaires, to reduce social influence on the outcomes. At the daycares, if a teacher was present they also sat behind the child. In an effort to stay consistent with current research in the field, a set, standardized task order was employed. The order was as follows: MEFS, Spin the Pots, Shape Stroop, Snack Delay, and finally the PDMS subtests. Fixed task orders are appropriate when assessing individual differences (Carlson & Moses, 2001). Anecdotally, due to the short duration of each task and subsequent tasks being unique and different from one another helped provide encouragement to continue. Therefore, we were not worried about fatigue in the later tasks. The experimenter emailed the parent a copy of the ECBQ short form to bring with them to the Motor Development Lab. The parent completed the CDI and demographics (Appendix A) throughout the testing session. The testing session lasted approximately 60 minutes.

CHAPTER 3: RESULTS

Upon analysis of the data, two outliers were found in the MEFS; each of these outliers were three times the mean of the values within the ¼ to ¾ inter-quartile range. Due to our small sample size, these outliers were included in the sample. Cronbach alpha tests show there was no coherence between the EF measures ($p = 0.11$), therefore we did not create a composite executive function measure. The mean, standard error and range for each variable are found in Table 1. The MANOVA showed no gender differences between the variables (F = 0.99; p = 0.50; df = 11).

Table 1: Summary of Means, Standard Error, and Range

	N	M	SE	Min	Max
Background					
Age (mo)	39	31.00	0.40	25.00	35.00
VI	34	58.44	4.36	1.00	98.00
ECBQ					
IC	31	4.45	0.17	2.50	6.50
EF tasks					
MEFS	38	14.53	0.98	5.00	41.00
SRE	38	7.03	0.41	3.00	12.00
Shape Test	35	2.24	0.22	0.00	3.00
Snack Test	32	3.72	0.10	1.00	4.00
FM tasks					
Grasping	39	41.82	0.26	39.00	48.00
VMI	38	104.84	1.18	84.00	119.00
FMQ	38	94.24	1.21	82.00	124.00

Abbreviations: VI = verbal intelligence; ECBQ = Behavior Questionnaire; EF = executive function; MEFS = Minnesota Executive Function Scale; SRE = spin reverse error score; FM = fine motor; VMI = visual motor integration.

Table 2 shows the results of the Pearson correlation analysis. Pearson correlations found significant, positive correlations between age in months and the MEFS ($p = 0.05$), age and visual motor integration ($p < 0.01$), MEFS and visual motor integration ($p = 0.04$), fine motor composite and grasping ($p < 0.01$), and fine motor composite and visual motor integration ($p < 0.01$).

Table 2: Bivariate Correlation Matrix

	1	2	3	4	5	6	7	8	9	10
1. Age (mo)	1									
2. VI	-0.22	1								
3. IC	0.18	0.17	1							
4. MEFS	0.32*	0.04	0.07	1						
5. SRE	0.11	0.03	0.35	0.00	1					
6. Shape	0.24	-0.10	0.27	-0.12	0.12	1				
7. Snack	0.20	-0.18	-0.22	0.30	0.30	0.06	1			
8. Grasp.	0.22	-0.07	-0.08	0.15	-0.03	-0.07	0.24	1		
9. VMI	0.49**	-0.03	0.13	0.34*	-0.12	0.11	0.20	0.19	1	
10. FMC	0.05	0.00	-0.11	0.17	-0.19	-0.04	0.23	0.73**	0.64**	1

df range from 24-35. Abbreviations: VI = verbal intelligence IC = inhibitory control; MEFS = Minnesota Executive Function Scale; SRE = spin reverse error score; Grasp. = grasping; VMI = visual motor integration; FMC = fine motor composite

* $p < 0.05$ ** $p < 0.01$

Next, we tested partial correlations controlling for age in months and verbal intelligence, shown in Table 3. The following measures were positively correlated: MEFS and visual motor integration ($p = 0.01$), fine motor composite and grasping ($p < 0.01$), and fine motor composite and visual motor integration ($p < 0.01$).

Table 3: Partial Correlation Matrix

	1	2	3	4	5	6	7	8
1. IC	1							
2. MEFS	-0.03	1						
3. SRE	0.36	0.16	1					
4. Shape	0.38	-0.05	0.13	1				
5. Snack	-0.04	0.06	0.28	0.30	1			
6. Grasp.	-0.32	0.17	-0.21	0.07	0.14	1		
7. VMI	0.00	0.57**	-0.09	-0.03	0.22	0.24	1	
8. FMC	-0.24	0.37	-0.24	0.05	0.23	0.85**	0.69**	1

Controlling for age (mo) and verbal IQ; Abbreviations: IC = inhibitory control; MEFS = Minnesota Executive Function Scale; SRE = spin reverse error score; Grasp. = grasping; VMI = visual motor integration; FMC = fine motor composite.

** $p < 0.01$

Using the enter method, we assessed the influence of fine motor skills on each executive function measure. In each model, age in months and verbal intelligence were added as controllers. The model for MEFS performance with the two control variables was not significant (F = 0.10) and did not account for much variability in MEFS performance (adjusted R^2 = 0.09). Next, we assessed the relationship between MEFS and the fine motor composite measure. This model was significant (F = 0.02), with an adjusted R^2 of 0.23. Finally, we aimed to identify if one of our fine motor measures was driving the relationship seen in the composite model. First, we tested each fine motor measure individually in each model, followed by adding both fine motor measures into the final model. Only the visual motor integration measure produced a significant model (F < 0.01; adjusted r^2 = 0.32), while grasping did not (F = 0.11; adjusted r^2 = 0.10). Our final model included age, verbal intelligence, grasping, and visual motor integration. This model was significant (F < 0.01; adjusted r^2 = 0.31); however, only the visual motor integration subtest was a significant predictor of performance on the MEFS (p < 0.01).

The results from this final regression analysis are shown in Table 4. No other executive function variable produced a significant model using this regression modeling procedure.

Table 4: Regression Analysis Predicting Performance on MEFS

Variable	**B**	SE **B**	β
Age (mo)	0.27	0.31	0.15
Verbal IQ	0.02	0.03	0.09
Grasping	0.32	0.39	0.13
VMI	0.34	0.11	0.51**

Abbreviations: VMI = visual motor integration.

** $p < 0.01$

CHAPTER 4: DISCUSSION

The goal of this study was to further explore the relationship between fine motor skills and EF in 2-year-old children. We found a positive relationship between EF and fine motor skills; however, this relationship was specific to only one aspect of fine motor skills – visual motor integration. In addition, only one of our EF measures, the MEFS, related to visual motor integration. The MEFS (our comprehensive measure of EF) was positively correlated with visual motor integration both before and after controlling for age and verbal intelligence. Regression analyses produced similar results, as visual motor integration was the only significant predictor of MEFS performance when our control variables and the grasping measure were also included in the model. None of our other EF measures nor the grasping measure produced significant correlations or regression models. Therefore, the main finding was that 2-year-old's ability to perform tasks requiring visual-motor integration was positively related to their overall EF skills.

Based on recent research in preschool age children, we expected to see positive relationships between fine motor skills and EF (MacDonald et al., 2016; Oberer et al., 2017; Wu et al., 2017). It appears we found a critical point in the development of these two factors. In 18-month-old children, Gottwald and colleagues (2016) found EF and fine motor skills were not correlated, only motor planning was related to EF (Gottwald et al., 2016). Wu and colleagues (2017) found fine motor skills, measured at 2-years-old, predicted performance on EF tasks at 3-years-old, with better fine motor skills predicting more mature EF (Wu et al., 2017). Our study provides evidence that fine motor skills and EF concurrently influence each other at an earlier age than previously shown.

Role of visual-motor integration versus grasping

As stated earlier, only the visual motor integration measure of fine motor control was related to EF. The grasping measure of fine motor control was not. One possible explanation for this difference could be how tasks within the two subtests were measured. In the grasping subtest, emphasis was placed on how the child completed the task. For example, whether the child used a pincer grasp when picking up a block. In the VMI subtest, emphasis shifted to the outcome of the child's actions, such as the height of tower a child was able to build from blocks.

In addition, the tasks within the VMI subtest seem to require more complex motor skills than those in the grasping subtest for 2-year-olds.

This notion of the differing complexity level of the motor skill has been shown to play a role in the relationship between EF and motor abilities. It has been hypothesized that complex motor tasks might require more cognitive attention to complete whereas simple motor tasks might require little or no cognitive attention to complete because they are more automatic (e.g., Willingham, 1998). Therefore, complex motor tasks, such as building block towers or manipulating scissors to cut along a line, likely require higher order cognition processes, such as EF, to control the coordination necessary for successful task completion (van der Fels et al., 2015). Accordingly, one might expect a strong relation between complex motor skills and EF skills, and no relation between simple motor skills and EF as we found in the current study. However, a recent study by Maurer and Roebers (2019) argues against this perspective. They found that both easy and difficult fine motor tasks were related to EF, but only difficult gross motor tasks, not easy gross motor tasks were related to EF. These findings suggest that fine motor task complexity might not play a role in this relationship with EF.

Therefore, a better explanation for our findings that visual-motor integration and not grasping was related to EF might be the fine motor skill itself. Numerous studies have found that the integration and coordination of visual and motor information are necessary for both motor and EF tasks and may be an important factor in the relationship between motor skills and EF (e.g., Cameron, Cottone, Murrah, & Grissmer, 2016; Maurer & Roebers, 2019). Therefore, it would make sense that our visual-motor integration measure would be related to EF whereas our grasping measure was not. In fact, in a study with 3- to 5-year-olds, MacDonald and colleagues (2016) found that early visual-motor integration skills are linked to later EF; whereas, object manipulation skills (similar to our grasping sub-tasks) were linked with social behaviors but not EF. It makes sense that the same could be true for our 2-year-old age group.

Another possible explanation as to why this relationship between EF and fine motor skills only existed for the visual motor integration measure and not the grasping measure is that the Peabody Developmental Motor Scale might not be the optimal scale for measuring fine motor development in 2-year-old children overall. The two fine motor subtests resulted in differing amounts of variability, possibly driving the relationships seen in our sample. We did not expect the grasping measure to produce such low variability (see Table 1). It became clear that one set of tasks in particular which required the children to manipulate a button strip was far too difficult for our children. No child was able to properly manipulate the button strip, leading to a ceiling effect. This ceiling effect likely drove any result between each EF measure and the grasping measure. Though the visual motor integration subtest produced more variability than the grasping subtest, a similar effect arose from tasks that did not seem appropriate for this age. For example, many children struggled with tasks involving the manipulation of scissors. After finishing the subtest, many parents noted that their children did not have any experience with scissors, in some cases, because parents had intentionally prevented their children from interacting with scissors. For future studies, it might be beneficial to utilize kinematic measures of fine motor control to better identify individual differences (e.g., Chen et al., 2010). For example, kinematic analyses of fine motor tasks like tower building may be more appropriate for distinguishing variability in fine motor skills than simply relying on a measure of success (e.g., the height of the tower the child can build).

Role of type of EF tasks

We expected to see fine motor measures predict performance on each of our EF measures; however, this was not the case. Only the MEFS measure was positively correlated with fine motor skill. The MEFS is a comprehensive measure of EF, which may capture the developmental level of these 2-year-olds more accurately than the other EF measures included in this study. Garon and colleagues (2008) noted that specific EF components develop along separate timelines. Using a measure specifically designed to measure EF as a whole construct may be necessary in 2-year-old children.

Although it was surprising that none of the EF tasks, other than the MEFS, were related to fine motor skills, there are some possible explanations for this finding. First, it could be the relationship between fine motor skills and EF is weak (van der Fels et al., 2015). In their review, van der Fels and colleagues identified fine motor skills and EF as one area requiring more research. Recent studies (MacDonald et al., 2016; Oberer et al., 2017; Wu et al., 2017) provide support for this link in early childhood, but it is possible this link may not exist later in children. In children approaching the pubescent age, the link between cognition and fine motor skills is weak or there is no relationship (Rigoli, Piek, Kane, & Oosterlaan 2012a; Rigoli et al., 2012b). These studies point to a dissipating relationship in children as cognition and fine motor skills continue to develop. It is possible some of our sample is at a stage in development where fine motor skills do not have a significant influence over individual components of EF, only EF as a whole construct. These concurrent influences of fine motor skills and the individual constructs of EF may only present after 3-years of age (e.g. MacDonald et al., 2017; Oberer et al., 2017). More research is needed in these younger children to confirm individual constructs of EF are not related to fine motor skills until 3-years-old.

Another possible explanation for these findings is that some of our measures of EF may not have been appropriate. All of our tasks which addressed a single component of EF were validated in 2-year-old children, but our sample produced higher success rates in the Shape Stroop and Snack Delay tasks than previously reported (Carlson, 2005). Overall, children performed well on these assessments, with many individuals receiving maximum scores. One explanation of this high performance could be due to the socioeconomic status of our sample. Parental education is a known mediator of socioeconomic status, and a child's subsequent EF, as children with higher educated parents display better EF than their peers who have less educated parents (Hackman, Gallop, Evans, & Farah, 2015). Our sample included highly educated families, which may account for this high performance.

We also have possible anecdotal explanations for these EF results. Children received goldfish for their stimulus for the Snack Delay task. It became evident that goldfish were not salient to the children in our sample. Parents selected the goldfish, with many parents noting that their child "loved goldfish"; however, the children did not seem excited by the goldfish. It could be that goldfish are too common/every day of a snack for this age group and that we needed to use a snack that was more enticing. Future studies could look at employing tasks validated for children older than the proposed sample, specifically in high socioeconomic samples. Pilot testing in delay tasks is likely necessary to ensure stimuli are salient for 2-year-olds.

Implications and conclusions

Our findings point to an important relationship between fine motor and EF skills at 2-years of age. Importantly, our results suggest this relationship may be driven by visual motor integration skills. Our results are correlational; therefore, we cannot conclude that developments in visual motor integration skills result in EF maturation. However, recent motor-based interventions with typically developing preschoolers have proven successful in improving EF (e.g., Mulvey, Taunton, Pennell, & Brian, 2018). Two-year-old children may represent a critical period in early development where fine motor skills can be utilized to improve EF to an even greater degree. Based on the embodied cognition approach, training up fine motor skills should allow 2-year-olds to improve their EF skills (e.g., Gibson, 1988; Smith & Gasser 2005; Thelen, 1995; Thelen, 2000). Studies providing infants with early motor experiences support this idea (e.g., Needham et al., 2002). For example, as mentioned previously, pre-reaching infants given “sticky mittens” which allow them to reach and grasp for objects earlier than normal show improved interest in objects (Needham et al., 2002). Given that our results suggest this relationship is stronger between EF and visual motor tasks, providing children with opportunities to utilize visual motor skills within their environment may promote further EF maturation and overall cognitive abilities. Future research should investigate the effect visual motor tasks have on the development of EF in 2-year-old children.

One promising intervention that has proven effective in preschool age children is block play. Schmitt and colleagues (2018) employed a semi-structured block play intervention in preschool age children aimed at improving performance in EF and mathematics. Over 7-weeks, children participated in 14 sessions lasting 15-20 minutes while working together in small groups to complete increasingly complex tasks given by the experimenter. Following the intervention, children who were given semi-structured block play improved more on their EF performance than the control group (Schmitt, Korucu, Napoli, Bryant, & Purpura, 2018). These improvements in performance could be due to improved fine motor visual-motor integration skills necessary for manipulating the blocks, though no measures of motor skills were taken in this study. Scaling a block-play intervention down to 2-year-olds may provide a fun, enriching environment for the development of fine motor skills and EF alike.

In conclusion, direct relationships between motor skills and EF seen in preschool age children are also present in 2-year-olds. This study shows visual motor skills predict comprehensive EF in 2-year-olds, after accounting for age, verbal intelligence. These results provide further support for the utilization of motor skills as a diagnostic measure or intervention protocol for differences in cognitive ability in early childhood for typically developing children. These findings further add to the growing body of literature defining the relationship between the development of EF and motor skills in early childhood.

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APPENDIX A.

Demographic Information

This information will be used to create norms for the area, adding to the strength and validity of the executive function assessments. If you are not comfortable filling any of the following questions out, feel free to leave them blank.

Child's Name: ____________________

Child's Date of Birth: ____________________ Gender: (Male) (Female)

Child's Height: ____________________ Child's Shoe Size: ____________________

Does your child receive special services at school/at home? (Yes) (No)

Ethnicity: (Native/Aboriginal) (Asian) (Hawaiian/Pacific Islander) (Black/African)
(White/Caucasian) (Hispanic or Latino)

Zip Code: ____________________ Caregiver's First and Last Name: ____________________

Is English the primary language spoken at home? (Yes) (No)

If no, please contact Lucas Rooney (lrooney@purdue.edu) before filling out other forms.

Language(s) Spoken at Home: ____

How many years of schooling have you completed? **(circle one)**

8th Grade or Less	Some High School	GED	High School Diploma	Some College
AA/AS Degree	BA/BS Degree	MA/MS	Doctoral/Postgraduate Degree	

How many years of schooling has your spouse/partner completed? **(circle one)**

8th Grade or Less	Some High School	GED	High School Diploma	Some College
AA/AS Degree	BA/BS Degree	MA/MS	Doctoral/Postgraduate Degree	

For the researcher: Participant #: ___________