HANDWRITING, LOOKING BEHAVIORS, AND NUMERICAL DEVELOPMENT

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Abstract

Destiny Stafford. Handwriting, Looking Behavior, and Numerical Development.

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Research on cognitive load and fine motor development suggests that children who struggle with writing automatically have less cognitive resources available for the symbolic aspects of numerical problem solving (Cameron et al., 2016). This thesis uses head-mounted eye-tracking technology to explore how children coordinate eye and hand movements as they attempt to copy single-digit numbers. Thirty-nine five- to six-year-old kindergarten children were presented nine single-digit and triple-digit stimuli to copy. Eye-tracking data was behaviorally coded for *look-forward* gazes and *look-back* gazes. A look-forward gaze refers to children looking ahead to the writing area before they had started writing whereas a look-back gaze refers to children looking back at the numerical stimulus after they had begun writing. Both gazes suggest an interruption in automaticity. Children then completed the Woodcock-Johnson IV Math Fluency and Letter Word Identification Achievement subtests. Regarding look-forward gazes, results indicated that there was a marginally statistically significant effect of gender where boys were gazing at the writing area slightly less than girls. With look-back gazes, findings indicated that children with higher math achievement scores tended to look back less frequently at the target stimulus. In contrast, children with higher reading scores tended to look back more frequently at the target stimulus. Findings suggests that kindergarten children are only starting to evidence automaticity and that letter competency does not equate to numerical competency. Therefore, children should have direct practice with number writing to enhance automaticity and school readiness.

Acknowledgments

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Handwriting, Looking Behavior, and Numerical Development

Introduction

Handwriting is a fundamental and essential skill that allows children to communicate and solve computational problems by improving memory and retention. Learning to write is a developmental skill that increases children's likelihood of future academic success across development (Longcamp, Zerbato-Poudou, & Velay, 2005). Specifically, the physical movement associated with handwriting plays a critical role in letter recognition and subsequent learning (Longcamp, et al., 2005). Recent work further supports this finding by suggesting that the specific regions of the brain associated with letter processing are more likely to be activated when participants are given writing practice (James & Atwood, 2009). Additionally, when children write rather than type letters, they become better at subsequent letter perception (James & Englehard, 2012). Importantly, letter copying in childhood is crucial for the early recruitment of letter processing in areas of the brain that are known to influence reading success (James Englehard, 2012). Together these findings suggest that writing letters increases children's understanding of letter types, which contributes to future reading success (James & Englehard, 2012; Longcamp et al., 2015; James & Atwood, 2009).

In contrast, research has not examined analogous questions about how the process of writing numbers is related to children's understanding of numerical symbols and thus how skill in writing numbers might be related to future math achievement. Therefore, it is crucial to understand how number writing might be related to math achievement. Without such knowledge, our understanding of numerical development is incomplete.

Fine Motor Skills and Math Achievement

Mathematics education begins early in formal school, and numerical abilities in kindergarten lay the foundation for success in future mathematic achievements (Duncan et al., 2007). Researchers have investigated potential non-academic indicators of academic achievement and have found that fine motors skills in early formal education are associated with future mathematics achievement (Grissmer et al., 2010). After comparing three nationally representative, longitudinal samples, Grissmer et al. (2010) found that strong fine motor skills at the start of kindergarten are related to mathematics achievement as late as early adolescence. Additionally, related work suggests that children with optimal fine motor skills are more likely to succeed in reading and math compared to children with poor motor skills (Cameron, Cottone, Murrah, and Grissmer, 2016). This emphasizes that skills involving visual-motor integration or small muscle movements, like those used in writing tasks, are predictors of mathematic achievement (Cameron et al., 2016). Despite the association between fine motor skills and future mathematic achievement, the underlying mechanisms behind this connection are still unclear.

Automaticity

Automaticity refers to the ability to write numbers automatically (Cameron et al., 2016). This skill greatly contributes to early mathematics achievement. Handwriting requires the coordination of manual and visual processes, and although this is a seemingly simple process, it takes practice to develop this skill. The first evidence of handwriting emerges during early childhood, and by age three, young children’s handwriting can be distinguished from drawing (Yamagata, 2007). However, while tracking the development of handwriting, researchers found that even at age five, only

22% of children had perfect scores on a letter writing task (Puranik & Lonigan, 2012). This suggests that handwriting is not developed fully at this age, and therefore children may need more practice writing before achieving fluency or automaticity with this skill.

Moreover, automaticity in letter writing may not develop until around the age of eight (Thibon, Gerber, & Kandel, 2018). Thibon et al. (2018) measured children, ages six to nine, in their cursive writing ability. The researchers used a digitizer that assessed duration, trajectory, number of velocity peaks, and mean velocity of writing to address automaticity. Their findings demonstrated that children's stroke number, or amount of pen lifts, while writing decreased as age increased. Stroke number affected the older children's production much less, suggesting they programmed information in chucks or whole letters. The stable stroke numbers for ages eight and nine may suggest that children have achieved automaticity in letter writing by age eight.

Cameron and colleagues (2016) argue that if children lack fine motor skills and struggle to write automatically, they are going to have less cognitive capacity available to engage in the symbolic aspects of higher order processes. Regarding number writing specifically, this suggests that when children can write numbers automatically, they will have more cognitive resources to dedicate to understanding mathematics. Since the cognitive load needed to solve mathematical computations may be influenced by how automatically children write, researchers should extend their understanding of handwriting to not only how children write letters but also how they write numbers.

Visual Manual Integration

Without knowledge of the number writing process, our understanding of handwriting and numerical development in young children is incomplete. The information gained from understanding the process of writing numbers could provide insights into the mechanisms that enable children to solve basic mathematical problems. To comprehend how the brain integrates visual and motor behaviors during handwriting, we must address the handwriting process in its entirety, instead of only focusing on the product of a handwriting task. Research has begun to assess the visual-manual process of writing numbers by implementing the use of eye tracking technology.

Research with eye-tracking has a century old history (Wade & Tatler, 2005). Recently, the use of eye-tracking has become more widespread due to the cost effective and low-effort tools that allow for an unobtrusive study of visual behaviors (Hartmann & Fisher, 2016). This methodology can be used to analyze human processing of visual information, such as eye-movements. Eye-tracking allows for an easily recordable amount of detailed information regarding the visual behaviors of individuals, which gives researchers insight into the underlying mechanisms of cognition and strategy choices during task execution. This information is otherwise not available when using an outcome, or product-based, measure such as response times or errors in task completion (Mele & Federici, 2012).

There are two key assumptions researchers follow when utilizing eye-tracking technology. The first is that gazing at a stimulus indicates it is likely the object of our thoughts, and the second refers to the assumption that time spent looking at a stimuli correlates to the time we think about these stimuli (Hartmann & Fisher, 2016). Despite the potential benefit of using eye-tracking to study numerical development, there have been far fewer eye-tracking studies for numerical cognition when compared to eye-tracking studies for language processing (Mock, Huber, Klein, & Moeller, 2016).

The primary basis for the current study arises from two prior studies examining the specific mechanisms that underlie handwriting and the role of looking behavior in this process. Maldarelli, Kahrs, Hunt, and Lockman (2015) used eye tracking technology to address the visual and manual processes children and adults use as they copy letter forms. The researchers asked 5-year-old children to copy single letters, three-letter words, and three-letter nonsense words. The results of this experiment demonstrated that relative to adults, children made more fixations to the three-letter nonsense words than to real words, implying that children are more efficient when they are familiar with the words they are copying (Maldarelli et al., 2015).

This research also found that prior to writing, children tended to make several fixations to letters in letter triads (2 fixations on 34.87% of trials, 3 fixations on 26.97% of the trials, and 4 or more fixations on 28.95% of the trials). However, this prior work did not examine fixations ahead to the writing area after looking at the stimuli. In the current research, we plan to address how measuring a look-forward gaze would be beneficial for understanding how children write numbers. Furthermore, during writing, Maldarelli et al. (2015) reported that children re-fixated to at least one letter of the exemplar during 89.09% of the trials, suggesting that children did not encode the entire stimulus completely when initially looking at it. Little is known, however, about how children initially visually encode numbers when attempting to copy them.

Subsequent research by Fears and Lockman (2018) also supports these findings by building upon Maldarelli et al.'s (2015) work. These investigators assessed the visual-manual integration of handwriting when copying familiar and unfamiliar letter forms. With the use of eye-tracking technology, the researchers investigated automaticity in preschool and early elementary school children's handwriting by measuring copying time, fixations, and pen lifts to address motor continuity. Fears and Lockman (2018) similarly concluded that children make a greater number of fixations to the unfamiliar Cyrillic symbols (M=1.72) used in this research, compared to familiar English letters (M=0.83). They also found that children made more visual fixations prior to writing than during writing, and that with unfamiliar words, children re-fixated their gaze during the act of writing, similarly to how children looked back at the stimuli during the Maldarelli et al. (2015) study. Both Maldarelli et al. (2015) and Fears et al. (2018) suggest that familiarity increases automaticity during handwriting. Furthermore, each study highlights the need for more research addressing looking behavior, specifically look-forward and look-back gazes, while writing.

The Current Study

The present research extends the literature on early handwriting by focusing on number copying, instead of letter copying. This research also considers how the process of writing numbers as well as the automaticity that comes with handwriting may relate to concurrent achievement in mathematics. Children in kindergarten ages five- to six-years-old were tested, similarly to the participants of the Maldarelli et al. (2015) and Fears and Lockman (2018) studies. To assess potential differences in learning experience, half of the participants were tested at the beginning of kindergarten and half were tested at the end of kindergarten.

The current project is part of a larger study looking at how children write single- and triple-digit numbers. Children were prompted to read and copy single-digit and triple-digit numerical strings. In the present work, we focus on single-digit trials only.

After the copying task, children completed three achievements tests presented in a random order: the Math Fluency subtest of the Woodcock Johnson Test of Achievement IV, the Letter-Word Identification subtest of the Woodcock Johnson Test of Achievement IV, and the Pair Cancellation subtest of the Woodcock Johnson Test of Cognitive Abilities IV. In the present study, we only include scores from the reading and mathematics subtests of the Woodcock Johnson Test of Achievement IV.

Through focusing on looking behavior, we expect to find patterns in the number of fixations children make as they copy single-digits. We assume a difference will arise in terms of the number of *look-forward* gazes and *look-back* gazes. A *look-forward* gaze refers to when children look ahead to the writing area before they start writing and after their gaze has rested in the exemplar area (the area with the target stimuli) at least once. A *look-back* gaze refers to when children look back at the numerical stimulus after they had begun to write and after their gaze has already rested on the writing area at least once. Each gaze type indicates an interruption in automaticity as seen through children pausing before writing i.e., a look-forward gaze, or bringing attention back to the initial exemplar while writing i.e., a look-back gaze.

Based on prior research (Maldarelli et al., 2015; Fears & Lockman, 2018), I predict that children tested in the fall of kindergarten, relative to those tested in the spring of kindergarten, will make a greater number of look-forward gazes to the writing area prior to writing. Additionally, I expect that children who have higher levels of mathematical ability will make fewer look-forward gazes to the writing area prior to writing. Similarly, I predict that children tested in the fall of kindergarten will make a greater number of look-back gazes to the writing area after they have begun writing, relative to those tested in the spring of kindergarten. Furthermore, I expect children who have higher levels of mathematic ability to make less look-back gazes to the numerical stimuli after starting to write. These hypotheses reflect the idea that the time in kindergarten increases practice with numbers and therefore influences the visual interruptions children may make with writing. These predictions also suggest that the more automatically children write numbers, the more mathematic competency they will possess. By finding patterns in visual-motor and numerical development, I will discover information about the building blocks of math learning. This knowledge could lead to new avenues of assessment for how children learn numbers as well as intervention regarding potential deficits in early handwriting, and how they relate to numerical development.

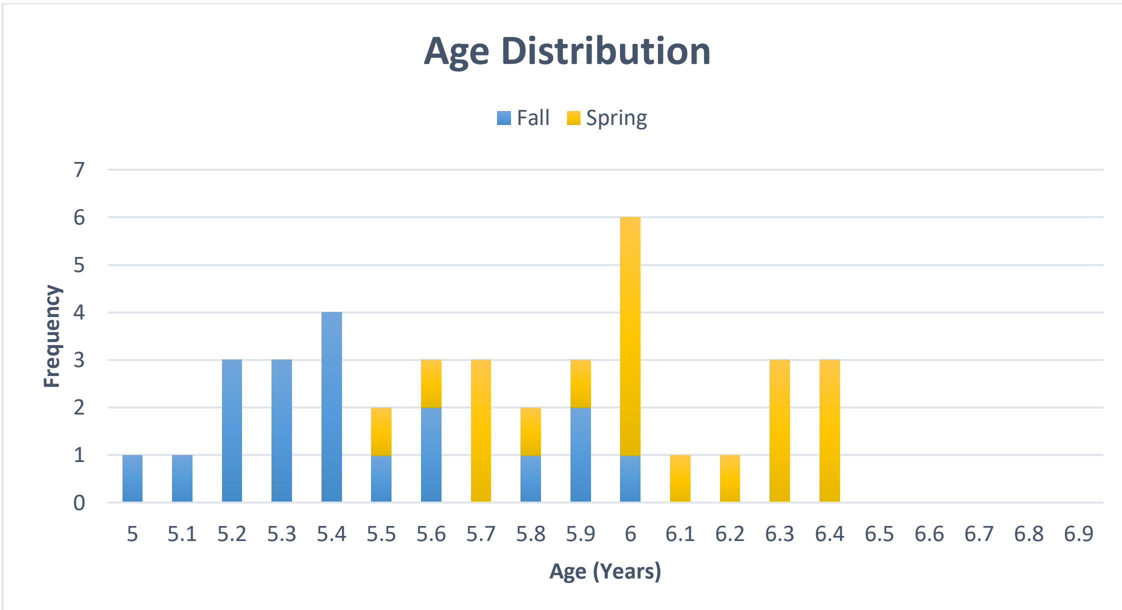
Method

Participants

Forty-three five- to six-year-old kindergarten children (M_{age}=5.79) who do not wear eyeglasses were recruited from elementary schools in the New Orleans Greater Area. Due to failing to complete the task or having poor calibration with the eye-tracker, four participants' data were excluded from the final sample. The final sample consisted of 39 participants, 19 children (M_{age}=5.49, SD_{age}= 0.28, 7 girls, 12 boys) who were tested in the fall of kindergarten and 20 children (M_{age}=6.07, SD_{age}=0.29, 9 girls, 12 boys) who were tested in the spring of kindergarten (see Figure 1). Most of the participants identified as White (White = 30, African American = 6, More than one race = 3).

Figure 1.

Participants Age Distribution in Years by Time Tested in Kindergarten



Note. Kindergarten children five- to six-years old were recruited and tested either in the fall at beginning of kindergarten or in the spring at the end of kindergarten. The left axis demonstrates the number of participants who are a particular age. The stacked sections of the chart depict the time when children were tested.

The study took place in Tulane's University Square at the Infant and Toddler Development Project lab. The Tulane International Review Board approved this study, and interested parents were contacted by phone or email to have data collected during a single testing session. Before participation, parents or guardians were required to give written consent for their child to undergo testing. Participants received a gift card or a t-shirt for participating.

Design

This study's design is an extension of previous work with letters and other symbols (Fears et al., 2018; Maldarelli et al., 2015) to numerical stimuli. The current study was conducted in two parts: a number copying task and the achievement tests. To measure the visual and manual behaviors that children use when writing numbers, children copied nine single-digit and nine triple-digit numerals, one at a time in random order. The numerical stimuli were displayed horizontally in an open binder with the stimulus located on the top half of the binder. The writing area where the children wrote their responses was located on the bottom half of the binder closer to the participant. Children proceeded to complete 18 trials of number copying. The children wore a Positive Science head-mounted eye tracker (Yarbus) throughout the number copying task to measure eye-movements while permitting the unobstructed use of their hands.

Procedure

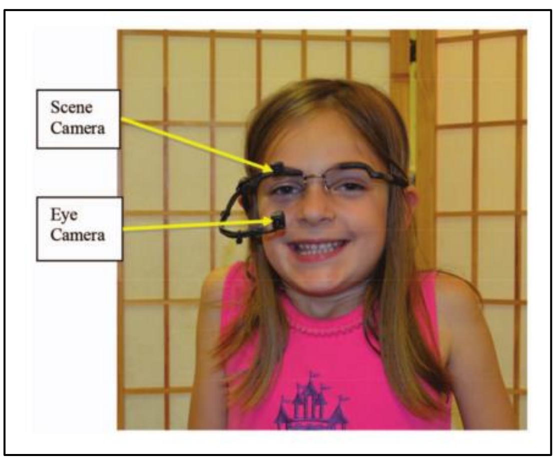
After receiving parental consent, the children participated in the testing session. The testing session consisted of the number copying task and the achievement tests. At the start of the number copying task the experimenter introduced parents and children to the eye-tracking technology, and then placed the eye-tracker gently on the child. The head-mounted eye-tracker was calibrated before and after the writing task (see calibration section below). During the writing task, children copied numerical stimuli. Following the copying task, participants completed two Woodcock Johnson Test of Achievement IV sub-tests in a random order: Math Fluency and Letter-Word Identification. These assessments determined whether looking behavior during the number copying tasks are related to subsequent academic achievement and cognitive abilities. The testing session lasted about 30 minutes, and children who needed a break during the session were granted a quick recess.

Eye-tracking

The first part of the study involved the use of eye-tracking technology. The participants wore a Positive Science head-mounted eye-tracker, which recorded their visual behaviors as they read and copied each numerical stimulus. The eye-tracker consists of two main components: a scene camera that records the visual field, and an infrared camera that records the participant's eye movements (see Figure 2). The eye and scene videos were recorded using PSLiveCapture software and processed with Yarbus software to create a scene video that revealed the direction of the child's gaze. The use of a head-mounted eye-tracker, as opposed to traditional eye-tracker systems that are mounted on a table or computer, allows for greater accuracy of looking behavior since the participant has unrestrained movement of their body and hands.

Figure 2.

Image of Child Wearing Head-Mounted Eye-tracking System



Note. Adapted from Maldarelli et al. 2015. Signed consent was received for use of this image.

Eye-tracking calibration.

Before the child began the number copying task, they were familiarized with the eye-tracking glasses. After the eyeglasses were placed on their head, the children participated in a calibration procedure to increase the accuracy of data recorded from the eye-tracker. Calibration procedures were modeled after the Fears et al. (2018) and Maldarelli et al. (2015) research. The process consisted of two calibration checks, one at the beginning of the number copying trials and another directly following the number copying trials. The calibration pages consisted of 12 possible calibration points distributed across the two pages in the open binder (6 points per page) and 6 possible validity points also distributed across the two pages in the open binder (3 points per page) ace). The calibration points appeared in the form of yellow and blue circles with a black dot in the center (see Figure 3), and the validity points appeared in the form of orange and blue circles. During the calibration procedure, participants were initially directed to look at the middle of each calibration point while keeping their head stationary, to emphasize only moving their eyes. Then, participants were prompted to mark the center of each calibration point with the tip of their pencil. Participants were asked to follow the same instructions with the validity points, which were used to check the calibration. During the second calibration check, children were prompted to repeat the calibration procedure performed during the start of the number copying task: first looking at the center of the calibration and validity points and then marking the center of each point with the tip of their pencil.

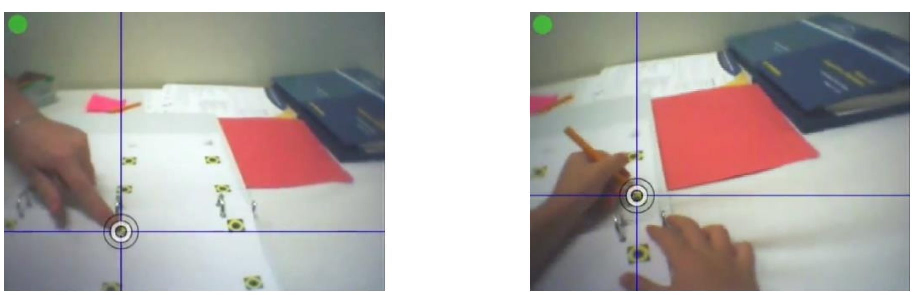
The eye-tracking videos were processed through the eye-tracking software (Yarbus) to determine the reliability and validity of the eye-track. For the calibration to be valid, the participant's eye-gaze had to rest within three or more of the six validity points during the calibration checks at both the beginning and end of the writing task. Two participants did not meet validity thresholds upon further review. One participant did not pass the validity check due to an absent corneal reflection, and another participant was excluded because the child moved the eye-tracking glasses immediately prior to the second validation check. Furthermore, a third participant was removed for failing to complete the tasks, and a fourth child was removed for having a poorly calibrated track of the looking behavior.

If a reliable and valid eye-track was obtained, gaze videos were exported from Yarbus to be behaviorally coded using the Datavyu software. Gaze videos included a fixation crosshair overlaying the scene videos indicating where the participant was looking while wearing the eye-tracker.

Figure 3

Images of the Calibration as Seen from the Yarbus Gaze Scene Video

a.) Initial Direction to the Point b.) Marking the Center of Point



Note. The calibration procedure consisted of two calibration checks: one at the beginning of the copying task and one at the end. During both checks, the participants were directed to look at the center and then mark the center of the 12 calibration points with their pencil. Then, participants were asked to repeat this procedure with the 6 validity points.

Number Copying Task

After eye-tracking calibration, the number copying task was administered. During the writing tasks, participants underwent 18 trials where they were asked to copy single- and triple-digit number sequences. Stimuli were presented horizontally in front of the children in an open binder. The binder was displayed in a landscape layout in front of the child such that the stimulus was on the top half of the binder furthest from the participant. The participant responded by copying the stimuli in the bottom half of the binder that was closer to the participant. During the start of the number copying task, the participant underwent a practice trial with punctuation marks (i.e., \?!) where they were asked to copy “what they see” in the top stimuli section.

Once the practice trial was complete, participants continued to copy the stimuli from the remaining trials in the number copying task. Two sets of the same stimuli were created, and order was counterbalanced across testing such that half of the participants received set A and half received set B. The stimuli consisted of numerals 1-9, and the triple-digit sequences were created from the numbers 1-3, 4-6, or 7-9. In the present study, only single-digit stimuli were analyzed. The writing task took approximately 10-15 minutes to complete.

Video Processing and Coding

Datavyu was used on a frame-by-frame basis of 20 frames per second to behaviorally code the calibrated videos from Yarbus. In Datavyu, the coders recorded the frequency of look-forward gazes before writing and the frequency of look-back gazes after writing to assess children’s planning and automaticity when writing numerical stimuli.

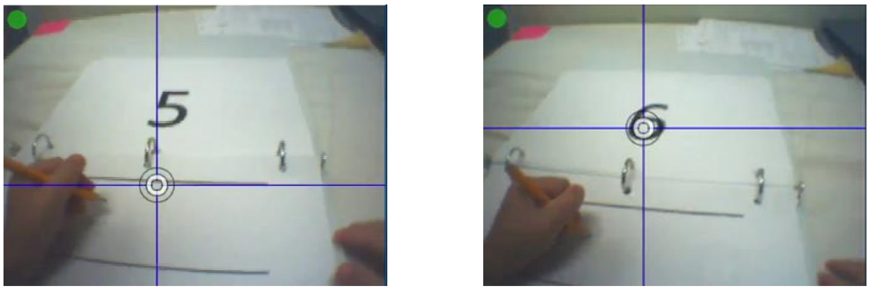
A look-forward gaze refers to gazes children make to the writing area prior to writing (see Figure 4a). A look-forward occurred each time the gaze entered the writing area 1) before the child started writing and 2) after the child had looked at the exemplar area at least once. These criteria accounted for children who were looking at the writing area at the end of the previous trial. The child was in the prior-to-writing phase the frame that the first numerical stimulus was fully visible to the participant until the last frame before the child began writing.

A look-back gaze refers to gazes children make looking back at the numerical stimulus after they have begun writing (see Figure 4b). To be considered a look-back, the gaze had to enter the exemplar area 1) after the child began writing and 2) after the child had looked at the writing area at least once. The child was in the during-writing phase the frame that the participant's pencil first touched the paper until the last frame that the child's pencil is touching the paper after they have stopped writing. Both gaze types suggest an interruption in automaticity. Two people double coded 20% of the gaze videos and found good reliability (Cohen's Kappa=0.78).

Figure 4

Images of Look-forward and Look-back Gazes as Seen from the Yarbus Gaze Scene Video

a.) Look-forward Gaze b.) Look-back Gaze



Note. A look-forward occurred when the child's gaze rested in the writing area (the bottom half of the binder) prior to writing (image a). To account for children who were looking at the writing area at the end of the previous trial, look-forwards were only counted after the child had gazed at the exemplar (the top half of the binder) at least once. A look-back occurred when the child's gaze rested in the exemplar area after writing. Similarly, to account for children who were looking at the exemplar as they began to write, look-backs were only counted after the child had looked at the writing area at least once (image b).

Achievement Measures.

Following the number copying task, participants were administered three achievement measures, which took about five minutes each to complete. After adding the time from the writing task, the testing session was approximately 30 minutes long.

Math Achievement.

Math achievement was evaluated using the Math Fluency subtest of the Woodcock Johnson Test of Achievement IV. This subtest required that participants promptly answer addition and subtraction problems within a set time limit (Schrank, Mather, & McGrew, 2014). The raw values (total number correct) from the Math Fluency subtest were standardized and entered into the analyses model building.

Reading Achievement.

Reading achievement was measured using the Letter-Word Identification subtest of the Woodcock Johnson Test of Achievement IV. The Letter-Word Identification subtest requires individuals to identify printed letters and words (Schrank et al., 2014). During this subtest, the children were presented with a series of letters and words and asked to read them aloud. The session ended when the child missed six words in a row. Consistent with the measure of math achievement, raw values (total number correct) from the Letter-Word Identification subtest were standardized and entered into model building.

Executive Function.

The Pair Cancellation subtest of the Woodcock Johnson Test of Cognitive Abilities IV was used to assess children's executive function. This subtest task required participants to find pairs of ordered items within a set time limit, while ignoring distractor items. Unlike the other achievement tests, the raw values (total number correct) from this subtest were recorded but not used in this study.

Results

The initial analysis examined single-digit trials based on success. Success was defined by whether children accurately copied the numerical stimuli. Out of 351 possible trials, children produced 327 (93.16%) correct responses during the single-digit trials (see Table 1). Example of the types of errors in number copying were adding extra features to numerals or writing the mirror of a numeral. Subsequent analyses focused on trials in which children successfully reproduced the exemplar stimuli.

Table 1

Percentage Correct by Single-Digit Numeral

Numeral	Percentage Correct
1	94.87%
2	97.44%
3	94.87%
4	87.18%
5	89.74%
6	94.87%
7	89.74%
8	94.87%
9	94.87%

Note: This table demonstrates how children had equally comparable rates of success when asked to write single-digit numbers.

Correct responses were analyzed using GLMM procedures with a Poisson distribution and a log link function in R. During model building, the categorical variables of gender (male or female) and time in kindergarten (fall or spring), as well as the continuous variables representing mathematics achievement and reading achievement were included in the model as fixed-effects (see Table 2). Furthermore, to account for by-subject variability and by-item variability, trial number and subject ID were entered as random-intercept predictors.

Table 2

Descriptive Statistics of Unstandardized Continuous Variables

	M	SD
Look-forward Gaze	01.27	00.90
Look-back Gaze	00.43	00.93
Math Achievement	07.52	09.90
Reading Achievement	21.29	12.05

Note: Math and Reading Achievement are not on the same scale and should not be interpreted as children having three times as better reading achievement than mathematics achievement on average.

Look-forward Gaze Analyses

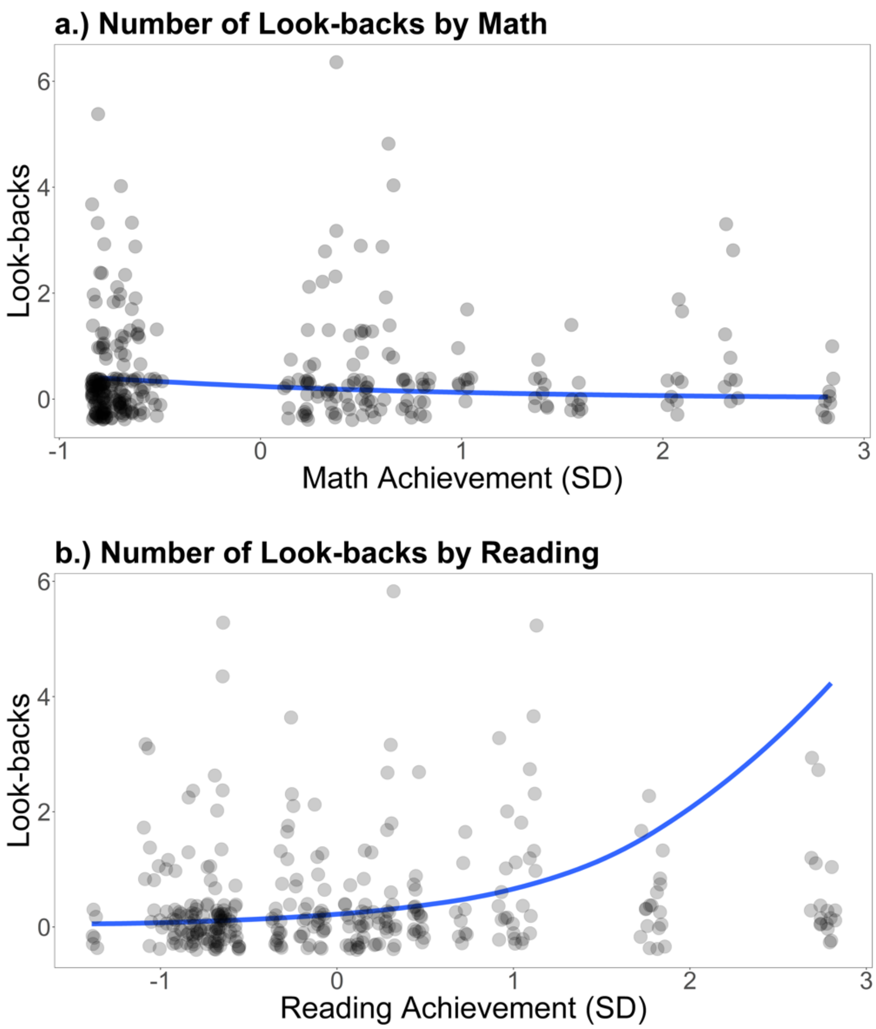
An analysis using GLMM procedures with a Poisson distribution and a log link function in R was run to assess how frequently children looked ahead at the writing area before they started writing and after they had looked at the target stimuli at least once. Before writing, children looked ahead to the target stimulus between 0-7 times (M=1.27, SD=0.90). This looking behavior indicates an interruption in planning as children were not automatically writing the stimuli but rather looking between the exemplar and writing area before they proceeded to write. Additionally, there was a marginally statistically significant effect of gender (β=-0.22, SE=0.12, $p=0.08$) with boys gazing at the writing areas slightly less than girls. However, the observed mean difference between the number of look-forwards boys and girls make was minimal (-.28 look-forward gazes). No other fixed effects were significant.

Look-back Gaze Analyses

Another analysis was run to evaluate the frequency at which children looked back to the target stimuli after they had started writing and after they looked at the writing area at least once. As children were writing the stimuli, they looked back at the target stimulus between 0-6 times (M=0.43, SD=0.93). There were significant effects of mathematics and reading achievement on the number of lookbacks children made. While writing, children with higher levels of reading achievement looked back more frequently at the target stimulus (β=1.06, SE=0.37, $p=0.005$). In contrast, during writing, there was a marginally significant effect of mathematics such that children with higher levels of math achievement looked back less frequently at the target stimulus (β=-0.64, SE=0.36, $p=.07$). Alternatively, time in kindergarten and gender were not significant.

Figure 5

The Relation Between Number of Look-back Gazes by Math and Reading Achievement (SD)



Note: Observed values are represented by shaded circles such that overlapping values appear darker. Circles are jittered to further distinguish overlapping scores. The predicted values for each fixed effect are represented by the blue line. As math scores increase children look-back slightly less frequently. As reading scores increase children look-back more frequently.

Discussion

The purpose of this study was to address the relationship between children's looking behaviors and their handwriting when copying single-digit numbers. Handwriting samples were analyzed for success as measured by copying the numbers correctly and for the relationship between the fixed effects of time in kindergarten, gender, mathematic achievement, and reading achievement, on look-forward and look-back gazes.

Looking Behavior

During testing, handwriting videos were behaviorally coded for look-forward and look-back gazes. A look-forward gaze referred to children glancing ahead to the writing area before they had started writing and after they had looked at the exemplar area at least once. Furthermore, a look-back gaze referred to children looking back at the numerical stimulus after they had begun writing and after they had looked at the writing area at least once. Each gaze type demonstrated an interruption in how automatically children were able to write numbers.

Results from the GLMM procedures suggest that there was a marginally statistically significant effect of gender regarding the look-forward gaze. This effect demonstrates that prior to writing girls gazed at the writing area slightly more than boys. The observed difference, however, was minor. It is possible that with larger samples this effect may not be as evident. Alternatively, there is some evidence that in early childhood education, teachers perceive girls as having lower math skills than those of their boy counterparts, which may further exacerbate early gender gaps in mathematic proficiency (Robinson-Cimpian, Lubienski, Ganley, & Copur-Gencturk, 2014). Ultimately further research on children's handwriting, gender, and mathematics is necessary.

Mathematics and reading achievement scores were related to the frequency of look-back gazes. While writing, children with higher levels of mathematic achievement tended to look back less frequently at the numerical stimulus relative to children with lower levels of mathematic achievement. Since children with higher math achievement copied numbers with fewer visual interruptions (i.e., with less look-back gazes), it can be assumed that automaticity with writing numbers may be present and could be associated with greater numerical competency.

This finding aligns with cognitive load research that suggests that children who struggle with writing numbers have fewer cognitive resources available for numerical problem solving than children who write numbers automatically (Cameron et al., 2016). One interpretation of this finding is that greater practice with writing numbers is necessary to increase numerical competency as automaticity is only beginning to appear in kindergarten children.

Additionally, reading achievement scores were related to look-back gazes. In contrast to math achievement, children with higher levels of reading achievement had more look-back gazes to the numerical stimulus. These results suggest that literacy competency itself does not translate to numerical competency. That is, children who have greater expertise when identifying letters and words do not necessarily have an advantage when writing numerical stimuli. In terms of preparing children for their academic futures, children need more explicit exposure and instruction writing numerals, beyond what they receive currently. Moreover, this instruction needs to be distinct from what they currently receive with reading and writing letters.

Lastly, there were no differences found regarding looking behavior and the time a participant was tested in kindergarten (i.e., in the beginning or at the end of the school year). It is possible children are already showing signs of automaticity while writing single-digit numbers by the start of kindergarten. This would account for the similarities in looking behavior despite participants being tested at different times.

Limitations

This study took place inside a university research lab environment. This environment does not offer the most naturalistic setting as children are normally copying numbers in a school setting. Although using a head-mounted eye-tracker increases the validity of the task, in a classroom environment, children may be dealing with distractions that may further tax cognitive load. These distractions could increase errors in automaticity giving different results than what were found in the research lab. Cameron et al. (2016) emphasizes the importance of children attaining the skills of writing automatically to have more cognitive resources for the symbolic aspects associated with writing. Another difference between the lab and school setting is found when looking at the number copying task itself. In classrooms, it is likely that numbers are presented in a different manner, whether that be in a smaller font or copying from a white board, rather than in large fonts on a page as it was shown in this experiment.

Although this study used eye-tracking technology in a new and inventive way, there is still room to be made in the quality of the technology and the coding platforms used to code gaze videos. For example, due to shadows or blurriness in the field of view, people may have trouble distinguishing aspects of the video when they are video processing and coding data.

Another limitation arises regarding the demographics of the final sample. When commenting on the highest level of education attained by participants' parents, only five participants had a parent whose highest form of education was a high school diploma. This means that most participants came from college-level or graduate-level educated parents. It is evident that a parent's education level could influence a family's social economic status which would impact a child's quality of life, the schools they may attend, and therefore even their skill when writing numbers. Furthermore, we did not assess whether children attended any early education programs, which could influence their exposure to numbers and subsequent proficiency in handwriting. These are all factors to take into consideration when discussing future directions as a more diverse sample could offer different insights regarding handwriting and number copying.

Future Directions

By kindergarten, children are five-to six-years of age. Some learning variabilities may have not presented themselves, been recognized by teachers, or been diagnosed by this time. Learning variabilities may influence the way children process information and therefore could impact the way children learn to write (Graham, 1999). These differences in visual processing may affect a child's written responses on the number copying task and achievement tests administered during this study. Future research could explore handwriting and eye-tracking technology specifically in children diagnosed with learning variabilities to assess if differences in looking behavior could be explored as a diagnostic tool.

The present research is part of a larger study on children's writing including both single- and triple-digit numerical sequences. Extending the current methodology to the analyses of the triple-digit trials, could give insights in how children encode and processes larger numbers. Previous research suggests that looking behavior differs across the magnitude of numerical stimuli. One study found that after participants performed a numerical comparison task addressing ratios, they made more fixations to larger ratio numbers relative to the smaller ratio numbers. This demonstrated people's attentiveness to larger number differences (Merkley and Ansari, 2010). The second study used eye-tracking technology to investigate how multi-digit numbers were perceived, and researchers found that children made greater fixations to larger entities and fewer fixations to smaller entities (Moeller et al., 2009). Thus, it is possible that children will make more look-forward gazes and look-back gazes to larger numerical entities, (i.e., triple digits), compared to smaller numerical stimuli, (i.e., single-digits, when completing a number copying task).

Conclusion

Handwriting is an essential skill needed for numerical development in children, and understanding the looking behaviors associated with writing numbers is critical for improving mathematic success. In this study, handwriting was primarily examined by looking at the different visual interruptions that children might make while writing numbers or developing automaticity. The findings indicated that kindergarten children are only just beginning to evidence automaticity when copying numbers. Additionally, the different frequency of look-back gazes among children who had higher math or reading achievement offered intriguing results about the relationship between writing automatically and academic competency. More broadly, the results about math and reading achievement suggest that reading proficiency, a measure of literacy, does not translate to numerical competency. Therefore, children should be given direct practice with number writing to enhance school readiness, improve numerical development, and promote automaticity.

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