Visual Processing and Spelling Development:

A Longitudinal Study

by

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Abstract

Writing is a skill that has become intertwined with daily life, and spelling is an essential skill for writing. In order to optimize the teaching of spelling, a detailed understanding of its development and the factors that affect that development is indispensable. Numerous influences on spelling development have been identified and studied in depth thus far, but one aspect that merits further consideration is visual processing. The present study employed a longitudinal structural equation modeling methodology in order to consider the concurrent and predictive effects of visual processing abilities on both spelling and orthographic processing. Results demonstrated significant concurrent and predictive relationships among these variables, primarily when children are in grades one and two. A significant predictive link was found between exogenous visual attention at the end of grade one and spelling at the beginning of grade two. Additional significant predictive relationships were found between coherent motion detection at the beginning of grade two and orthographic knowledge at the end of grade two as well as between exogenous visual attention at the beginning of grade two and orthographic knowledge at the end of grade two. Concurrent relationships were found, but were limited to grade one. These results have implications for the theoretical understanding of the influence of visual processes on the development of both spelling and orthographic knowledge. Furthermore, these results could potentially contribute to the development of an intervention for spelling that includes a magnocellular dorsal stream training component.

Keywords: spelling, orthographic knowledge, coherent motion detection, exogenous visual attention, longitudinal research.

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Efficient written communication is an essential skill in today's society. Writing allows people to express thoughts, ideas, and desires to others with whom they are unable to communicate directly. Whether it is completing an assignment for school, taking notes, sending emails, completing reports for work, interacting on social media, sending text messages, or any number of other tasks and activities, people write every day. And in order to be able to write, one must be able to spell. Not only is spelling important for daily life, it is also beneficial to the development of other valuable skills including reading and vocabulary (Bourassa & Treiman, 2014). Given the importance of spelling, it is no wonder that children are taught to spell from an early age, and are encouraged to continue developing their spelling skills throughout their lives. Obtaining an understanding of how spelling develops and what factors have an effect on its development is an important undertaking so that students' acquisition of this skill can be optimized. It is unfortunate then that spelling is frequently disregarded by both researchers and granting agencies when compared to other aspects of language development such as reading (Joshi, Treiman, Carreker, & Moats, 2008-2009). An aim of the present study is to contribute to the limited but ever-expanding knowledge base regarding the development of children's spelling ability.

Development of Spelling Ability

Information on how children acquire spelling skills is extremely valuable and is one of the most crucial areas of spelling research. It is through understanding the way children learn to spell and what skills typical children can be expected to have at a given age that educators are able to tailor the learning experience to their needs. The world is filled with writing and exposure to writing begins at a very early age. There is writing on buildings, street signs, food packaging and many more places, and this writing does not escape the notice of even very young children. Because of the ubiquity of writing, preschoolers come to recognize some of the aspects that characterize writing even before they are able to form proper letters. At this point, children can be observed "writing" by making marks with some form of writing utensil. Though this writing does not resemble any known alphabet or other writing system, it still can easily be distinguished from the child's drawing (Treiman & Bourassa, 2000). Furthermore, Lavine (1977) found via a card sorting task that children as young as three years old are able to distinguish writing from drawing. The same study determined that by the age of five, children can tell the difference between actual Roman letters and pretend letters with similar characteristics (Lavine, 1977).

Beginning from these basic understandings about writing, children develop more sophisticated views as they age and gain experience. An important concept that children who are learning to spell need to grasp is the alphabetic principle, the understanding that the words and letters people write represent the things they say (Zaretsky, Core, & Currier, 2010). While research varies on the exact age at which children develop this understanding, it is generally accepted to typically be in place around kindergarten (Zaretsky, Core, & Currier, 2010; Treiman & Bourassa, 2000). As children receive formal instruction in spelling, they begin to make use of various forms of linguistic knowledge to inform their spellings. These include phonology (knowledge of the sounds of a language), orthography (knowledge of permissible letter sequences), and morphology (knowledge of relations among words and grammatical influences on spelling). Early spelling research largely focused only on how children can make use of phonological knowledge when spelling, but more recently studies have shown that from a very young age children possess orthographic and morphological knowledge as well, and are able to make use of that knowledge to produce more accurate spellings (Bourassa & Treiman, 2014). Furthermore, as children mature, they are able to grasp and apply more and more complex linguistic rules when trying to spell words (Bourassa & Treiman, 2014).

Of particular interest for the present study is orthographic knowledge. Given that orthography consists of a language's rules regarding which letters may be placed next to each other, it is easy to see how knowing these rules would be indispensable for accurate spelling. Children can begin to use their orthographic knowledge when spelling from an early age, and the extent to which they can grasp orthographic concepts and the sophistication with which they are able to apply them continue to develop over time. Kindergarteners are able to comprehend certain basic orthographic principles, such as that a word needs a vowel (e.g., "werp" is more word-like than "bzlt") (Rosinski & Wheeler, 1972). By first grade, students can typically identify allowable and unallowable doublets (e.g., "noss" is more word-like than "novv") (Cassar &

Treiman, 1997) and consonant clusters (e.g., “pilt” is more word-like than “pibk”) (Cassar et al., 2005). These sorts of rules are rather straightforward, but as students get older, they are able to apply more complex orthographic conventions to their spellings.

Many sounds can be represented by multiple spellings. For example, two options to write out /k/ would be “k” or “ck”. When making a decision on which to use, it is helpful to consider contextual information by examining the rest of the word. Continuing with the /k/ example, if the /k/ sound is preceded by a long vowel, the short “k” spelling should be used (e.g., “jeek” is more word-like than “jeeck”). However, if that same /k/ sound is preceded by a short vowel, the long “ck” spelling should be used (e.g., “jeck” is more word-like than “jek”). This type of contextual orthographic knowledge can be found in children by the second grade (Hayes, Treiman, & Kessler, 2006). It is interesting to note that the use of this information can vary not only with age, but also with spelling ability. It has been demonstrated that good first grade spellers were able to grasp contextual orthographic conventions whereas poor first grade spellers were not (Shebaylo & Bourassa, 2018). The ability to use orthographic knowledge in spelling continues to develop even further as children move through school. By grade six, they are able to recognize that syllabic stress can affect a word’s spelling. To illustrate this concept, consider the pseudowords “verliting” and “verlitting”. Both appear as though they could be perfectly legitimate words, but the correct spelling depends on whether emphasis is placed on the /vər/ syllable or the /lɪt/ syllable. Bourassa and Bargen (2013) found that sixth graders are able to make this distinction.

Factors Affecting Spelling Development

A comprehensive understanding of the development of children’s spelling ability requires investigation into the factors by which it is affected. Some predictors of spelling development have already been well established by past research such as reading ability, phonological processing, and rapid naming (Plaza & Cohen, 2007). Another set of predictors which have considerable evidence to back them up, but still require more research are visual processes such as motion detection and visual attention. Research has indicated that a relationship between these visual processes and spelling exists, but many of the details surrounding that relationship remain obscure. In particular, information regarding how visual processes influence spelling throughout development is scarce and much needed.

Looking more specifically at visual attention, it is a broad topic comprised of several related but distinct processes. It can be broadly divided into two types, endogenous visual attention which involves sustained attention, focused attention, visual search, and tracking, and exogenous visual attention which involves attention shifting and attention capture (Yantis, 2014). There is evidence that each of these types of visual attention is related to spelling development, but for the purpose of this study, only exogenous visual attention (EVA) will be considered. The reason only EVA is being examined in this project is that it is consistent with the theoretical framework through which the relationship between visual attention processes and spelling can be understood. This theoretical framework and the literature backing it up will be considered in detail momentarily.

The goal of the present study is to establish whether visual processes, specifically motion detection and EVA, can predict growth in a child's spelling ability and orthographic knowledge, and if so, to determine if the strength of this effect varies with age. To this end, a longitudinal design will be used following children from grade one to grade three. This particular age range will be very informative because it is a critical period for the acquisition of spelling skills as was discussed previously. In this study, children who attend public schools in the city of Winnipeg, Manitoba are being examined. Reviewing the Manitoba curriculum for these ages, it is clear that significant changes in the spelling skills that children are expected to develop occur during this stage. In grade one, children are taught to "use sound-symbol relationships and visual memory to spell familiar words," (Government of Manitoba, n.d.). Throughout second grade, students learn how to "Spell familiar words using a variety of strategies [including phonics, structural analysis, and visual memory] and resources [such as personal dictionaries, classroom charts, help from others...]," (Government of Manitoba, n.d.). And finally, by the end of third grade, children should ideally "know and apply conventional spelling patterns using a variety of strategies [including phonics, structural analysis, and visual memory] and resources [such as junior dictionaries, electronic spell-check functions...] when editing and proofreading," (Government of Manitoba, n.d.). These curricular goals show that during the period of development being examined and in the Manitoban school context, significant changes are expected in students' spelling ability, their knowledge of the rules of language, and the strategies they use to produce accurate spellings.

Magnocellular Dorsal Stream Deficit Theory

The most commonly accepted explanation as to why a deficit in visual processing could be a contributing cause to a deficit in spelling ability is the magnocellular dorsal (MD) stream deficit theory. In order for a person to make sense of the world they see, visual information that is collected by the eyes must be interpreted by the brain. Light enters the eyes and stimulates different types of cells on the retina. These different cells transmit this information to the magnocellular, parvocellular, or koniocellular layers of the lateral geniculate nucleus (LGN). From the LGN, transmission of visual data follows one of two main pathways. One is the ventral pathway, sometimes called the “what” pathway, which processes signals from the parvocellular and koniocellular layers. It is through this pathway that information on things such as an object’s colour or form is processed. The other is the dorsal pathway also known as the “where” or “how” pathway. This stream processes information from the magnocellular layers of the LGN. Through this pathway, information pertaining to an object’s motion and location is obtained, information that is used to guide action (Yantis, 2014).

While it may seem at first glance like the ventral stream would be more important to spelling in order to recognize the form of letters, it is in fact poor functioning of the MD stream that has been found in a subset of poor developing spellers (Cornelissen & Hansen, 1998; Vidyasagar & Pammer, 2009; Kassaliete et al., 2015), and there is a compelling case to be made as to why this is. While this study does not directly examine brain activity, it is nevertheless important to understand the neurological mechanism behind the phenomena being discussed in order to confidently interpret any observations made. The MD pathway leads from the retina and LGN through area V5 (also called the middle temporal (MT) area) of the brain, an area involved in motion detection (Zeki, 2015). Because it passes through this area, a deficit in the pathway is often characterized by poor motion detection (Zeki, 2015). After area V5, the MD stream leads to the posterior parietal cortex (PPC), an area of the brain associated with EVA (Itti & Koch, 2001; Qian, Den, Zhao, & Bi, 2015) and the coordination of visual-motor interactions (Yantis, 2014). A deficit in the magnocellular pathway could hinder the transmission of visual information to this area. Recall that the MD pathway is commonly known as the “where” pathway. If a person who is trying to learn and remember how to spell a word is not receiving proper information along the “where” pathway, remembering where each letter is supposed to go in that word may prove to be a real challenge. Accordingly, it has been found that some people who have impairments in EVA, an important function of the MD pathway, also have issues with letter position encoding (Kinsey, 2004; Cornelissen & Hansen, 1998) which would undoubtedly make it difficult to spell words correctly.

If the MD stream deficit theory of spelling difficulty is true, a number of observations should be able to be made. To start, it should be the case that poorer spellers tend to show greater deficits in motion detection, EVA, and letter position encoding as compared to better spellers. Additionally, if this is a process that affects children throughout even some portion of their development, then each of these elements should show malleability and growth as children age. The literature demonstrating the above points will now be examined in detail.

Coherent Motion Detection

Motion detection is the ability to visually perceive the movement of objects. While not assumed to directly affect spelling, this aspect of visual processing is regarded as one of the best indicators of MD pathway functioning (Zeki, 2015). This ability has been known to take a long time to fully develop, though the reason for this remains unclear (Bogfjellmo, Bex, & Falkenberg, 2014). In a study conducted with 103 participants aged 6-17, researchers found that global motion perception develops gradually throughout childhood, reaching maturity around age 14 (Bogfjellmo, Bex, & Falkenberg, 2014). A separate study with a far larger sample of 2,027 children aged 7-18 found similar results. In this case, it was once again found that motion detection improves gradually in this period of development; however, the researchers in this second study found that growth did not plateau at any point in their age sample (Kassaliete, Lacis, Fomins, & Krumina, 2015). Regardless of which of the two has the right of it, both are in agreement that during the earlier period of development, the period being examined in the current study, motion detection develops gradually and continually.

Having established that motion detection is an ability that can and does grow during the early years, the next step is to demonstrate that it is related to spelling and orthographic processing. Some of the earlier research on this topic was published in 1998 by Cornelissen and Hansen. They measured participants' coherent motion detection (CMD) as well as their ability to choose the correct spelling of a word when given the choice between it and an anagram (e.g., "ocean" or "ocaen"). The findings of this experiment indicated that persons who had poorer motion detection were more likely to make certain types of errors on the word choice task (Cornelissen & Hansen, 1998). More recent evidence can be found in a longitudinal study assessing CMD and spelling ability. The study showed that CMD in kindergarten was a significant predictor of a child's spelling ability in grade three (Boets, Vandermosten, Cornelissen, Wouters, & Ghesquière, 2011). The link between motion detection and orthographic processing was demonstrated in an fMRI study conducted in 2015. The researchers demonstrated that the brain areas associated with motion detection (area V5 and the PPC) were associated with orthographic awareness, but not phonological awareness (Qian et al., 2015). Though this particular study was conducted with Chinese adults (a population that differs from Canadian children who are being examined in the present study), it still establishes the link between motion detection and orthographic processing.

Exogenous Visual Attention

Next, EVA involves the automatic aspects of visual attention such as attention shifting and capture that are determined by external factors. A study concerning the development of this ability was carried out with seventy-four six to ten year-old children. The results indicated that relative to the younger participants, the older participants demonstrated reduced reaction time for automatic attention orienting (Lellis et al., 2013). Though EVA is well established as early as infancy, it develops even further all the way through adulthood. The malleability of visual attention is given further support by studies showing it is influenced not only by a child's age, but also experience. Dye and Bavelier (2001) found in their sample of seven to twenty-two year-olds that along with improving with age, visual attention improved depending on whether the participant played action video games regularly.

In the 1998 Cornelissen and Hansen study discussed above, it was suggested that a potential factor that could link motion detection and letter position encoding may be attentional processes. They found this particularly compelling due to the MD pathway's involvement in attention (Cornelissen & Hansen, 1998). While not specifically EVA, Plaza and Cohen (2007) were able to establish that visual attention in general influences spelling development in the early school years. However, though the relationship they found was strong at first, it decreased significantly in strength after the first grade (Plaza & Cohen, 2007). Although there are not many studies that look explicitly at the relationship between EVA and spelling, there is nevertheless sufficient evidence to expect that one exists. First of all, because of the involvement of the PPC in EVA and because the PPC is part of the MD pathway (Itti & Koch, 2001; Yantis, 2014), a relationship between EVA and spelling would be consistent with the MD deficit theory of spelling difficulty. Furthermore, the PPC has been associated with both orthographic processing (Qian et al., 2015) and letter position encoding (Kinsey, 2004). Difficulty with EVA could be seen as an indicator of impaired functioning of the PPC which would in turn impede its other functions. Finally, there are several studies linking EVA to the development of word-reading skill (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012; Vidyasagar, 2004; Hari, Renvall, & Tanskanen, 2001). Since reading research frequently parallels spelling research in the area of visual processing and since the same MD stream deficit theory has been offered to explain the reading difficulties faced by some children (Vidyasagar & Pammer, 2009), it can be expected that the relationship will be present with spelling as well.

Finally, letter position encoding is the mechanism proposed to tie this puzzle’s visual processing pieces to its linguistic pieces. Much like the two visual processing abilities discussed previously, letter position encoding too has been shown to develop over the period of childhood this study is concerning itself with. A study by Ktori & Pitchford (2009) with ninety-six Greek or English children of either six or nine years of age found that the nine year-olds performed far better on a task that assesses letter position encoding than the six year-olds. This age range is consistent with the first through third grade students of the present study, showing that this skill too is one that is changeable during this key stage. Moreover, as can be expected from the nature of the abilities, letter position encoding has been directly linked to spelling ability (Fischer-Baum, McCloskey, & Rapp, 2010).

Intervention Studies

Further evidence for the relationship between visual processing and spelling can be seen in the work of Teri Lawton. Lawton (2011) conducted an experiment to determine if improving children’s magnocellular functioning could lead to improvements in their reading and writing. She found that after three months of direction discrimination training, the reading and spelling skills of the participants improved significantly (Lawton, 2011). Further evidence of this comes from a lab in Italy that has done substantial research on action video game playing and reading ability. They found that action video game training can significantly improve children's motion detection and reading abilities (Gori, Seitz, Ronconi, Franceschini, & Facoetti, 2016). This implies that a child's level of magnocellular functioning has a direct effect on his or her ability to read and spell. On the other hand, it does not appear as though the reverse is true. A lab in the United States examined in multiple studies whether improving reading ability could improve magnocellular functioning. However, they have as of yet been unable to find significant results (Joo, Donnelly, & Yeatman, 2017). This shows that MD functioning does not appear to be influenced by exposure to reading.

Present Study

To assess the effects of visual processes, specifically CMD and EVA, on the development of spelling ability, a longitudinal research design will be used. Data from an existing database were collected at five occasions following participants from the first grade to the third grade. At each of these five waves of testing, measures of participants' CMD, EVA, spelling, and orthographic processing abilities were gathered. The hypotheses proposed in this study are considered under these circumstances.

Hypotheses

Based on the evidence and background information discussed above, three hypotheses will be made. First, it is expected that both CMD and EVA will be concurrently related to both spelling and orthographic knowledge at each wave of testing. The relationships between CMD and spelling (Cornelissen & Hansen, 1998) and between CMD and orthographic processing (Qian et al., 2015) have been established in previous studies, so it is reasonable to expect to find such a relationship here as well. As for EVA, the link has not been so clearly shown. However, due to consideration of the MD stream deficit theory and the associated neurobiology (Itti & Koch, 2001; Yantis, 2014), the association of PPC functioning with orthographic processing (Qian et al., 2015) and letter position encoding (Kinsey, 2004), and the association of EVA with reading (Franceschini et al., 2012; Vidyasagar, 2004; Hari, Renvall, & Tanskanen, 2001), it is expected that this concurrent relationship will be found.

Second, it is anticipated that both CMD and EVA will be able to predict growth in both spelling and orthographic knowledge from each wave of testing to the subsequent wave. There are four primary reasons why this is expected. First, as discussed in relation to the first hypothesis, it is expected these variables will all be significantly related to one another. Next, there is evidence that CMD (Bogfjellmo, Bex, & Falkenberg, 2014; Kassaliete et al., 2015), EVA (Lellis et al., 2013; Dye & Bavelier, 2001), spelling (Treiman & Bourassa, 2000), and orthographic knowledge (Cassar & Treiman, 1997; Cassar et al., 2005; Hayes, Treiman, & Kessler, 2006) all improve over the period of development being examined here. There is also evidence that improving magnocellular functioning can improve spelling ability (Lawton, 2011). And finally, there is evidence of a relationship between CMD and spelling (Boets et al., 2011) and between visual attention and spelling (Plaza & Cohen, 2007).

Finally, it is hypothesized that while the predictive relationships will be present throughout all the waves of testing, those relationships will be stronger at the earlier waves. Research addressing this specific question is scarce, but the literature that is available points towards visual processing having its greatest influence on spelling early on. Plaza and Cohen (2007) found that visual attention is a significant predictor of spelling in grade one, but not in grade two or three. As children attend school, receive formal instruction, and are able to access spellings and word representations more automatically, other processes related to language may predominate and visual processes may decrease in importance. Past research has found that language based abilities such as phonological awareness, rapid naming, and morphological/syntactic skill are significant predictors of spelling at the end of grade two, which is around the midpoint of the present study (Plaza & Cohen, 2004).

Methods

Participants

The study began with 171 first grade children (94 male and 77 female) recruited from Winnipeg public schools. Participants were tested at five occasions over the course of three years. Some students were unable to participate in the full five waves of the study and by the final wave of testing, 137 students remained. Mean age of participants was 71.50 months at the beginning of the study and 96.63 months at the end of the study. For demographic information including participants' socioeconomic status (SES) and first language, please refer to Table 1 in Appendix B.

Procedure

The students who participated in this study were assessed using a series of tests that measure different aspects of spelling and visual processing. Testing was carried out in a quiet room in the students' schools. The same tests were administered at each of the five waves of data collection. The first wave of testing occurred in the spring during which the participants were in grade one. The following waves occurred during the autumn of grade two, the spring of grade two, the autumn of grade three, and finally the spring of grade three. There were intervals of approximately six months between each occasion participants were tested.

Materials

Some of the tasks were completed using paper and pencil while others were done on a computer. For the computer based tasks, participants were seated in front of a 17 inch Sony SDM-X73 LCD monitor with a refresh rate of 60 Hz, a display resolution of 1280 x 1024 pixels and a pixel response time of 16 ms. The monitor was connected to a Macintosh G4 power book laptop. The computer based tasks were programmed using VPixx software (VPIXX Technologies Inc., 2009). For the purpose of minimizing distractors, controlling for variations in ambient lighting, and ensuring a constant distance between the participant and the screen, participants viewed the monitor with a 57 cm hood attached.

Wide Range Achievement Test: Spelling Subtest

The spelling subtest of the Wide Range Achievement Test, third edition (WRAT-3) was used to assess spelling ability. During this test, participants are read words aloud which they are then asked to write down. The test continues until participants either reach the end of the list (40 words) or spell 10 words incorrectly at which point their raw scores are recorded (Wilkinson, 1993). Reliability was found to be good to excellent for the spelling measure across all the waves of testing (wave 1, $\alpha = .83$; wave 2, $\alpha = .82$; wave 3, $\alpha = .86$; wave 4, $\alpha = .89$; wave 5, $\alpha = .91$).

Word Likeness Judgement

The Word Likeness Judgement task is a test of orthographic processing (Siegel et al., 1995; Cassar & Treiman, 1997). During the task, participants are shown forty pairs of pseudowords (i.e., made-up words) that can be divided into four categories. Word pairs differed in terms of orthographic cuing and phonological cuing. A pair with a high degree of orthographic cuing will have one word that more closely follows spelling rules than the other. A pair with a high degree of phonological cuing will have one word that is more pronounceable than the other. Thus, four categories emerge: high orthographic cuing and low phonological cuing, high phonological cuing and low orthographic cuing, high levels of both types of cuing, and low levels of both types of cuing. When presented with a pseudoword pair, the participants are asked to identify which of the two looks more like a real word. Pseudowords are used for this task in order to control for any effect prior experience with real words. After the participants complete the task, their score is calculated based on the number of correct responses given. Whereas the WRAT-3 spelling test assesses the productive, recall aspect of spelling, the word likeness judgement task assesses recognition of orthographic rules. Reliability was generally a little low on the Word Likeness Judgement measure, but showed a trend of improvement across waves (wave 1, $\alpha = .42$; wave 2, $\alpha = .56$; wave 3, $\alpha = .62$; wave 4, $\alpha = .56$; wave 5, $\alpha = .65$). Please refer to Appendix A for a list of the items used for the Word Likeness Judgement task.

Random Dot Kinematogram

The Random Dot Kinematogram (RDK) is a widely used test of CMD (Raymond & Sorensen, 1998; Cornelissen & Hansen, 1998) which is the most commonly employed measure of MD stream functioning (Zeki, 2015). This is a computer based task that requires participants to indicate whether the majority of the 150 white dots on the screen are moving up or down. In each trial, a certain number of dots move in the same direction while the remaining dots move in random directions producing “white noise” movement. Each trial consists of seven frames shown for 32 ms each. With each frame, the dots move in either the target direction or a random direction. The participant’s task is to indicate verbally in which direction he or she believes the majority of the dots appear to be moving. To remove the possibility of participants electing to focus on one particular dot, each dot is only present for two frames, with new dots being added to replace them.

Scores for the RDK denote a participant’s dot coherence threshold. This threshold represents the minimum amount of dots that must be moving in the same direction for a participant to respond correctly at least 75% of the time. The participants’ thresholds are determined using parameter estimation by sequential testing, a technique through which the program considers a participant's performance on previous trials to determine the percentage of dot coherence to set for subsequent trials. With each trial, the program calculates the participant's threshold and a confidence interval for that threshold. This process continues either until a 95% confidence interval is obtained or 100 trials are completed. Because a higher threshold indicates that a participant required more dots to be moving in the same direction in order to answer accurately, lower scores on this task correspond to better performance. As this is the opposite of the other tasks in this study, this must be kept in mind when interpreting the results. Reliability was low for the first wave of RDK testing, but very good for the remaining waves (wave 1, $\alpha = .63$; wave 2, $\alpha = .81$; wave 3, $\alpha = .85$; wave 4, $\alpha = .84$; wave 5, $\alpha = .82$).

Data for the RDK task were collected twice during the first wave of testing and three times at each other wave. Younger children were overwhelmed by three repetitions of the task due to fatigue and issues with concentration. For this reason, the task was done only twice at the first wave to maximize the accuracy of obtained scores.

Line Motion Illusion

The line motion illusion (LMI) task measures EVA, specifically attention capture (Hikosaka, Miyauchi, & Shimojo, 1993). Like the RDK, this task is also computer based. Participants are presented with a screen showing a fixation point in the centre and a dark background with four squares, one in each quadrant of the screen. At the start of each trial, one of the squares was lit up briefly. Following either a short (0 ms), medium (16 or 50 ms), or long (120 ms) delay, a gray line appeared across the screen connecting the cued box and the box horizontally adjacent to it. The participant was instructed to indicate in which direction the line appears to be moving. Although the line does not move whatsoever, if the participant is able to quickly orient his or her vision to the cue, the line appears to be moving away from that cue.

LMI scores were calculated by averaging the frequency of reported rightward movement for left side cue conditions across stimulus onset asynchronies (SOAs) and averaging the frequency of reported leftward movement for right side cue conditions across SOAs. Calculated in this way, higher scores indicate stronger experience of the illusion which indicates better EVA. Then, a score obtained from a set of trials in which the line actually did move was subtracted from that average score (proportion "rightward" movement responses from the rightward animation lines, and proportion of “leftward” movement responses from the leftward animation lines). This was done in order to control for any inattention or bias participants had to answer in a particular way (e.g., a tendency to answer “left” for most trials). Reliabilities were acceptable to good across waves of LMI testing (wave 1, $\alpha = .81$; wave 2, $\alpha = .72$; wave 3, $\alpha = .82$; wave 4, $\alpha = .76$; wave 5, $\alpha = .79$).

Data Analysis Methods

Statistical analyses were completed using IBM SPSS Statistics version 27 and MPlus version 8.4. In order to test the hypotheses specified in this study, a longitudinal structural equation modeling (SEM) approach was taken. SEM is a useful tool for analyzing longitudinal data and evaluating the questions posed in this study because it provides both a global overview of how well a given set of relationships fits the data and also a close look at the strength of individual relationships between variables.

Latent Variable Identification

A cornerstone of SEM analysis is the use of latent variables. A latent variable is a measure of a particular construct that is produced using multiple sources of information, called indicators. Latent variables were created for each construct of interest in this study, including spelling and orthographic knowledge as outcomes and CMD and EVA as predictors. Items from the WRAT-3 spelling subtest were divided into two groups (even-numbered questions and odd-numbered questions) and these were used as the indicators of spelling ability. Items on the word likeness judgement task were used as indicators of orthographic knowledge. Test items were allocated into one of four groups according to their level of orthographic and phonological cuing. To most accurately capture orthographic knowledge, items in the two conditions that included high orthographic cuing were used as indicators. CMD was measured multiple times at each wave of testing using the RDK task. Each estimate of CMD (two estimates for the first wave and three for each other wave) was used as an indicator of CMD. Finally, for EVA, two attention indices, one that averaged performance on right side cued trials of the LMI task and one that averaged over left side cued trials, were calculated at each wave of testing. These attention indices were used as the indicators for EVA. Analysis of the indicators revealed that all of the latent variables used in this study feature strong indicators. For a summary of the statistics associated with each of these indicators, please refer to Table 2 in Appendix B.

Evaluating Model Fit

There are two approaches to evaluating model fit that are typically used by researchers, the statistical rationale and the modeling rationale (Little, 2013). The statistical rationale relies solely on the χ^2 statistic. While χ^2 is the standard indicator of fit, it is often problematic in SEM studies. The issue with this statistical rationale is that χ^2 is heavily influenced by both sample size and degrees of freedom and as a result, χ^2 is almost always significant when SEM is used (Little, 2013). Therefore, it is more informative to use the modeling rationale instead. This approach involves evaluating how well a model approximates the data by examining a number of absolute and relative measures of fit (Little, 2013). Accordingly, in this study, two measures of absolute fit (the root mean square error of approximation (RMSEA) and the standardized root mean square residual (SRMR)) and two measures of relative fit (the comparative fit index (CFI) and the Tucker-Lewis index (TLI)) will be considered. In using these measures to evaluate model fit, the thresholds for good model fit described by Hooper, Coughlan, and Mullen (2008) will be used. These thresholds are RMSEA < 0.07, SRMR < 0.08, CFI > 0.95, TLI > 0.95 (Hooper et al., 2008).

Competing models will be evaluated to determine which has the best fit taking into account both a statistical perspective and a conceptual perspective. A statistical test known as the $\Delta\chi^2$ which calculates whether two models provide significantly different fit by comparing the difference between their χ^2 statistics will be used (Werner & Schermelleh-Engel, 2010). In this comparison, it is a smaller χ^2 value that indicates better fit.

Missing Data

Over the course of the study, 34 participants were lost due to attrition. The primary reasons for this were children moving to different schools (and so not being available for subsequent testing occasions), or children being ill on the day of data collection. To account for missing data in this study, full information maximum likelihood (FIML) estimation was used in order to make use of all available data (Enders, 2010). FIML can be improved by the inclusion of an auxiliary variable (i.e., a variable that is not included in the analysis but that is correlated with the variables that are included in the analysis). The elision subtest of the Comprehensive Test of Phonological Processing, a measure of phonological awareness, was used as an auxiliary variable. Phonological awareness was chosen due to its well established link to spelling and other linguistic abilities (Treiman, 1991; Diamanti et al., 2020) and because it was highly correlated with both spelling ($r = .69$, $p < .001$) and orthographic knowledge ($r = .84$, $p < .001$) in this study.

The data were assessed to determine whether there was any systematic pattern to the missing data. A series of *t*-tests was completed to compare the initial spelling and orthographic knowledge scores of the group of participants with missing data to those of participants who were present for the full duration of the study. It was determined that there was not a significant difference between the two groups on either of the spelling indicators (spelling indicator 1: $t(169) = .691$, $p = .167$; spelling indicator 2: $t(169) = .855$, $p = .077$) or on either of the orthographic knowledge (OK) indicators (OK indicator 1: $t(169) = .980$, $p = .612$; OK indicator 2: $t(169) = 1.913$, $p = .341$). Thus, the missing data were determined to be missing at random.

Results

Descriptive Statistics

Descriptive statistics including number of participants (*N*), means, and standard deviations (SD) of each indicator at each time point are presented in Table 3. Patterns of improved performance on all measures across waves are generally indicated.

Table 3

Descriptive Statistics

	Wave 1		Wave 2		Wave 3		Wave 4		Wave 5	
	N	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD)	*N*	Mean (SD
S1	171	1.78 (1.39)	150	2.75 (1.68)	153	3.78 (2.05)	139	4.64 (2.35)	135	5.25 (3.00)
S2	171	1.56 (1.29)	150	2.40 (1.49)	153	3.26 (1.84)	139	4.09 (2.20)	135	4.78 (2.66)

OK1	171	6.08	151	6.56	153	6.88	139	7.26	135	7.21
		(1.62)		(1.40)		(1.51)		(1.43)		(1.47)
OK2	171	7.06	151	7.47	153	8.04	139	8.48	135	8.51
		(1.53)		(1.69)		(1.60)		(1.56)		(1.50)
CMD1	170	53.44	156	42.52	155	42.59	140	41.35	135	37.87
		(26.85)		(27.21)		(26.92)		(26.52)		(24.72)
CMD2	170	54.57	154	45.90	154	46.20	139	42.60	136	39.79
		(30.04)		(27.26)		(27.04)		(25.62)		(26.51)
CMD3	-	-	151	44.43	154	46.10	140	39.81	134	37.02
				(28.24)		(28.33)		(25.86)		(24.56)
EVA1	170	.28	156	.31	155	.43	137	.46	137	.30
		(.28)		(.34)		(.29)		(.31)		(.31)
EVA2	170	.28	156	.30	155	.39	137	.39	137	.23
		(.29)		(.35)		(.32)		(.31)		(.37)

Note. S = Spelling total scores (1: odd-numbered items, 2: even-numbered items); OK = Orthographic Knowledge total scores (1: high orthographic and low phonological cuing items, 2: high orthographic and high phonological cuing items); CMD = Coherent Motion Detection percentage coherent-movement (1, 2, and 3 correspond to the order in which estimates were determined within a session); EVA = Exogenous Visual Attention, attention index scores (1: left-side cues, 2: right-side cues).

Fully Specified Model

Initially, a model was tested that included all of the variables and links that tested every hypothesis specified in this study (pictured in Figure 1 in Appendix C). However, this model included far too many free parameters as compared to the available number of observations and as a result, the model was under-identified and, therefore, not interpretable. To overcome this issue, the study was split into two outcomes. These outcomes considered the effects of the visual processing variables (CMD and EVA) on spelling and orthographic knowledge separately. This course of action was chosen because spelling and orthographic knowledge are consistently treated as two distinct abilities in the literature and because none of the hypotheses specified in this study considered the relationship between these outcomes.

Outcome 1: Spelling

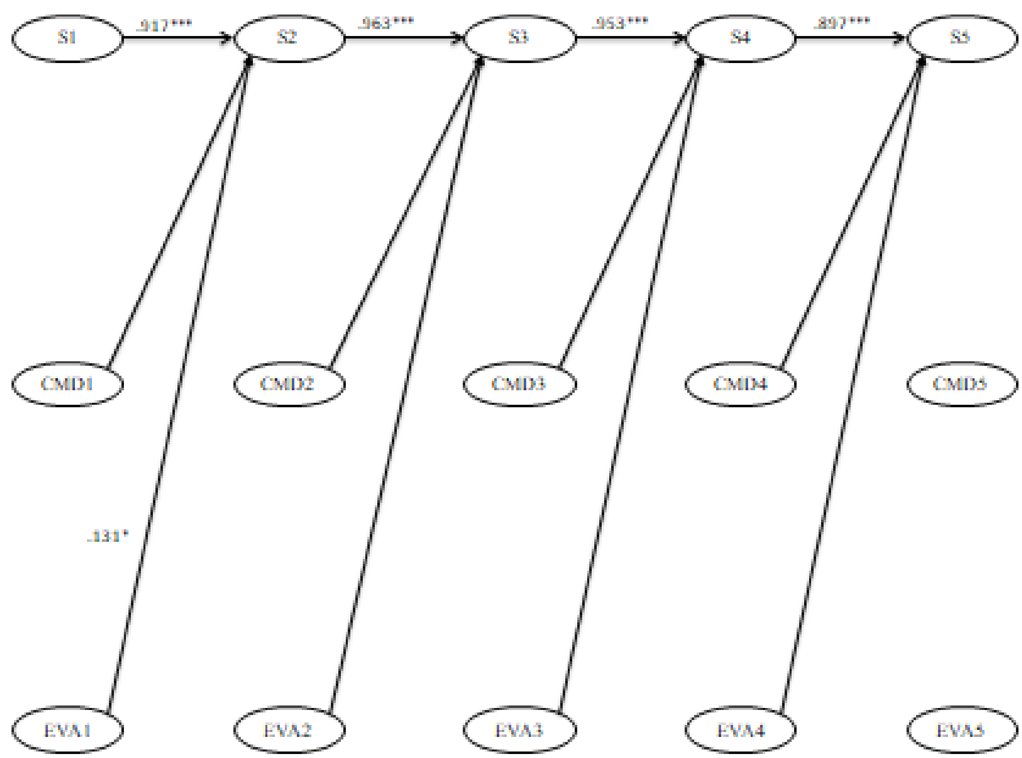
A series of models was tested to determine the set of relationships among variables that best fit the data. For a summary of the fit statistics produced by each model, please refer to Table 4. In all of the models, each variable was allowed to correlate freely with each other variable across time points. First, a Baseline Model was established. This model included only the autoregressive links for spelling from one wave of testing to the next and as such allowed consideration as to whether adding additional links contributed to better model fit. This model is shown in Figure 2 in Appendix C. As would be expected due to its high degree of parsimony, this produced very good model fit (see Table 4).

Next, a more complex model (Model 1) akin to the original fully specified model above was run to examine potential roles of the visual processing factors. This model included autoregressive links for all of the variables across each wave, predictive links from CMD in a given wave to spelling in the subsequent wave across all waves, predictive links from EVA in a given wave to spelling in the subsequent wave across all waves, and concurrent links between all variables at a given time point. This model is pictured in Figure 3 in Appendix C. The RMSEA showed good fit for this model; however, the other fit statistics were all slightly below the threshold values considered to indicate good fit (see Table 4). Furthermore, this model had significantly poorer fit than the baseline as shown by a χ^2 difference test ($\Delta\chi^2 = 94.81$; $df = 24$; $p < 0.001$).

The final model tested included only the links that were necessary to test the hypotheses described in this study. Those links were the autoregressive effects for spelling and the predictive links from CMD or EVA in one wave to spelling in the next. Including autoregressive links for the spelling variable is important to control for past spelling ability. In this way, only influences of the visual processing variables were considered in the predictive links. This model is shown in Figure 4. The model showed very good fit with all the fit statistics examined (see Table 4). It also fit the data significantly better than the previous model that was tested (Model 1) ($\Delta\chi^2 = 104.53$; $df = 32$; $p < 0.001$). While this model did have slightly better fit statistics than the Baseline Model, this difference was not statistically significant ($\Delta\chi^2 = 9.72$; $df = 8$; $p = 0.285$). However, this final model is considered the best fit for the data because of its strong fit statistics and because it is more informative than the baseline model.

Figure 4

Final Spelling Model (Model 2)



Note. S = spelling, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to wave of testing. Variables were allowed to correlate freely; however, these correlations have been left out of the figure for the sake of clarity. For a summary of the correlations, see Table 5.

† = p < .1; * = p < .05; ** = p < .01; *** = p < .001.

Table 4

Fit Statistics for Outcome 1 Models

	χ^2	*df*	RMSEA	SRMR	CFI	TLI	$\Delta\chi^2$
Baseline	610.52	468	0.042	0.052	0.960	0.952	
Model 1	705.33	492	0.050	0.102	0.940	0.932	
Model 2	600.80	460	0.042	0.047	0.961	0.952	

Difference between Baseline and Model 1	24	94.81 (***)
Difference between Baseline and Model 2	8	9.72
Difference between Model 1 and Model 2	32	104.53 (***)

Note. RMSEA = root mean square error of approximation, SRMR = standardized root mean square residual, CFI = comparative fit index, TLI = Tucker-Lewis index.

† = $p < .1$; * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

All of the autoregressive links for spelling were highly significant, indicating a significant predictive effect of past spelling performance on future spelling performance and stability of spelling ability over the course of the study. While all variables were allowed to correlate with one another freely, those links were left out of the diagram to avoid clutter. Instead, please refer to Table 5 for a summary of these relationships. Significant correlations were found between CMD from a given wave and CMD at each other wave. The same pattern was found for EVA. Additionally, the majority of the waves of CMD and EVA were found to be significantly correlated with spelling at wave one. Correlations between CMD and EVA across waves of testing were inconsistent with few correlations being significant. Nevertheless, all significant correlations were in the expected directions. Finally, a significant predictive link was found between EVA at wave one and spelling at wave two; the coefficient for this link is included in the model. All other predictive links were not significant.

Table 5

Outcome 1 Correlations

	S1	CMD1	CMD2	CMD3	CMD4	CMD5	EVA1	EVA2	EVA3	EVA4	EVA5
S1	-										
CMD1	-.307**	-									
CMD2	-.232**	.575***	-								
CMD3	-.161†	.653***	.630***	-							
CMD4	-.355***	.751***	.595***	.866***	-						
CMD5	-.309***	.659***	.736***	.873***	.934***	-					
EVA1	.083	-.034	-.053	-.049	-.219*	-.180†	-				
EVA2	.273**	-.076	.019	-.212*	-.115	-.161	.243*	-			

EVA3	.235**	.017	-.095	-.075	-.183†	-.184†	.442***	.496***	-		
EVA4	.215*	.026	-.118	-.059	-.108	-.147	.522***	.428***	.670***	-	
EVA5	.293**	-.085	.029	-.049	-.050	-.029	.255*	.436***	.520***	.577***	-

Note. S = spelling, CMD = coherent motion detection, EVA = exogenous visual attention.
† = p < .1; * = p < .05; ** = p < .01; *** = p < .001. Digits correspond to the wave of testing.

Outcome 2: Orthographic Knowledge

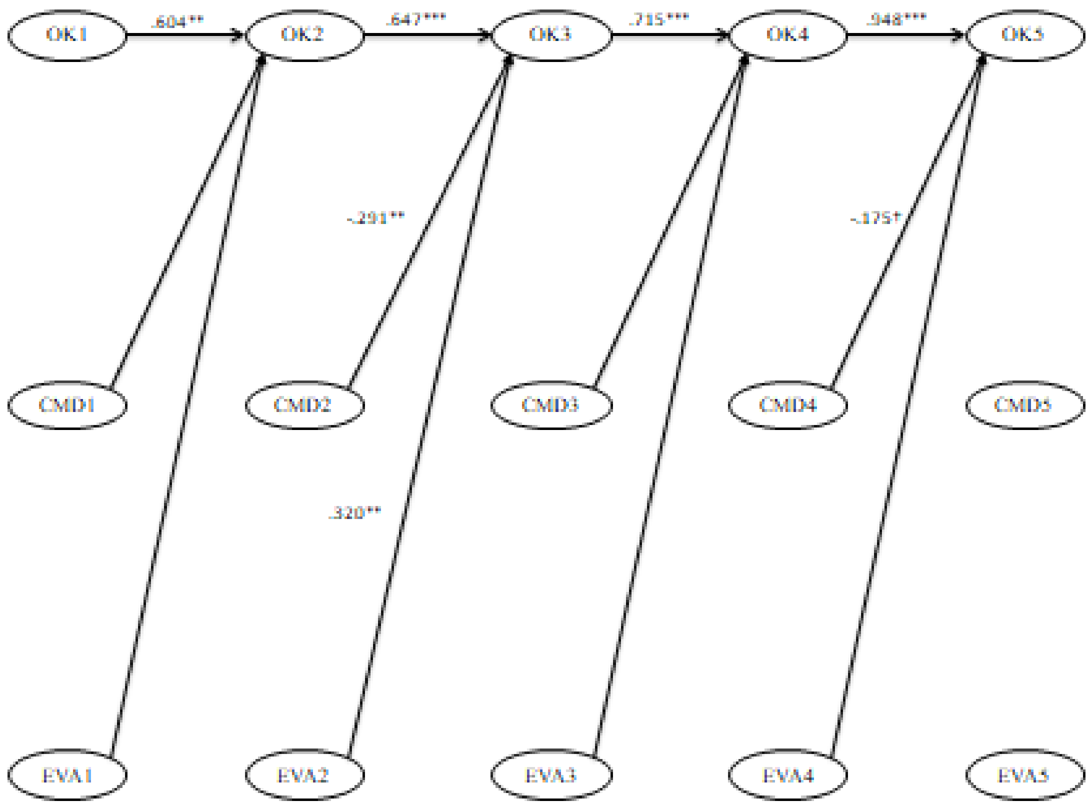
A similar approach to that of the spelling analysis was followed in the analysis of the orthographic knowledge data. Again, a series of models was tested and those models were compared to determine which fit the data best. Fit statistics for each of the orthographic knowledge models are summarized in Table 6. The Baseline Model for Outcome 2 included only the autoregressive relationships for orthographic knowledge. Please refer to Figure 5 in Appendix C for a diagram of this model. The absolute fit statistics (RMSEA and SRMR) showed good fit for this model and the relative fit statistics (CFI and TLI) were close to the threshold for good fit (see Table 6).

The next model that was assessed was similar to the fully specified model that was originally hypothesized. It included autoregressive links across all waves for all variables, predictive links from CMD and EVA at one wave of testing to orthographic knowledge in the next wave, and concurrent relationships between all variables at a particular wave of testing. For a diagram of this model, please refer to Figure 6 in Appendix C. The RMSEA showed good fit for this model while the other fit statistics were all approaching the threshold (see Table 6). This model showed significantly poorer fit than the Baseline Model as shown by a χ^2 difference test ($\Delta\chi^2 = 73.94$; $df = 24$; $p < 0.001$).

One additional model was tested that included only the links necessary to test the hypotheses specified in this study. Those links were the autoregressive links for orthographic knowledge and the predictive links from CMD and EVA at one wave of testing to orthographic knowledge in the next. This model is shown in Figure 7. Most of the fit statistics indicated good fit for this model while the TLI was nearing the specified threshold (see Table 6). This model was a significantly better fit for the data than both the prior model (Model 1) ($\Delta\chi^2 = 92.76$; $df = 32$; $p < 0.001$) and the Baseline Model ($\Delta\chi^2 = 18.81$; $df = 8$; $p = 0.016$). Therefore, this model was determined to be the best fit for the orthographic knowledge data.

Figure 7

Final Orthographic Knowledge Model (Model 2)



Note. OK = orthographic knowledge, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to wave of testing. Variables were allowed to correlate freely; however, these correlations have been left out of the figure for the sake of clarity. For a summary of the correlations, see Table 7.

† = p < .1; * = p < .05; ** = p < .01; *** = p < .001.

Table 6

Fit Statistics for Outcome 2 Models

	χ^2	*df*	RMSEA	SRMR	CFI	TLI	$\Delta\chi^2$
Baseline	584.89	469	.038	.061	.946	.936	
Model 1	658.83	493	.044	.091	.923	.912	
Model 2	566.08	461	.037	.056	.951	.941	
Difference between Baseline and Model 1		24					73.94 (***)
Difference between Baseline and Model 2		8					18.81 (*)
Difference between Model 1 and Model 2		32					92.76 (***)

Note. RMSEA = root mean square error of approximation, SRMR = standardized root mean square residual, CFI = comparative fit index, TLI = Tucker-Lewis index.

† = $p < .1$; * = $p < .05$; ** = $p < .01$; *** = $p < .001$.

The autoregressive links for orthographic knowledge were all highly significant indicating stability of orthographic knowledge across time points as well as a predictive effect of past orthographic knowledge on future performance. As with Outcome 1, the correlations were left out of the diagram in order to maintain a legible figure. The correlations for this model are summarized in Table 7. Similarly to Outcome 1, correlations between CMD at one wave and CMD at other waves and correlations between EVA at one wave and EVA at other waves were all significant and positive. CMD at wave three was significantly correlated with EVA at wave two. A few other correlations between CMD at a given wave and EVA at a given wave were approaching significance, but most were not significant. In addition, the majority of the waves of CMD and EVA were significantly correlated with orthographic knowledge at wave one. Significant predictive links were found between CMD at wave two and orthographic knowledge at wave three and between EVA at wave two and orthographic knowledge at wave three. The link from CMD at wave four to orthographic knowledge at wave five was approaching significance. All other predictive links tested in this model were not found to be statistically significant.

Table 7

Outcome 2 Correlations

	OK1	CMD1	CMD2	CMD3	CMD4	CMD5	EVA1	EVA2	EVA3	EVA4	EVA5
OK1	-										
CMD1	-.395*	-									
CMD2	-.335*	.576***	-								
CMD3	-.338**	.652***	.631***	-							
CMD4	-.491***	.751***	.598***	.867***	-						
CMD5	-.488***	.650***	.746***	.875***	.940***	-					
EVA1	.206	-.024	-.067	-.040	-.200*	-.165	-				
EVA2	.376**	-.080	.014	-.202*	-.111	-.178†	.204*	-			
EVA3	.326*	.023	-.093	-.076	-.186†	-.191†	.445***	.484***	-		
EVA4	.299*	.028	-.128	-.060	-.114	-.150	.549***	.437***	.670***	-	
EVA5	.491***	-.092	.014	-.065	-.057	-.040	.289**	.461***	.517***	.580***	-

Note. OK = orthographic knowledge, CMD = coherent motion detection, EVA = exogenous visual attention.

† = p < .1; * = p < .05; ** = p < .01; *** = p < .001. Digits correspond to the wave of testing.

Discussion

This study was designed with the purpose of investigating the potential predictive effects of visual processing factors (CMD and EVA) on the development of spelling and orthographic knowledge. This relationship is supported by the MD stream deficit theory of spelling difficulty. The MD stream deficit theory posits that a deficit in the transmission of visual information along the MD pathway may impact spelling ability by impairing letter position encoding. This theory has been supported by several studies (Cornelissen & Hansen, 1998; Vidyasagar & Pammer, 2009; Kassaliete et al., 2015), but more evidence is needed to establish longitudinal relationships. Because CMD (Zeki, 2015) and EVA (Itti & Koch, 2001; Qian et al., 2015) are known to be reliant on areas of the brain along the MD pathway, these were considered to be good estimators of MD stream functioning. Past research has found associations between each of these visual processes and spelling and orthographic processing (Boets et al., 2011; Qian et al., 2015; Lellis et al., 2013; Cornelissen & Hansen, 1998).

Using structural equation modelling, hypotheses based on the above information were tested. After testing a series of models, two final models were determined: one testing the influence of the visual factors on the spelling outcome and one testing their influence on the orthographic knowledge outcome. Three hypotheses were made and they were the same for both outcomes. It was hypothesized that:

1. The visual measures would be concurrently related to the outcome variables at each time point.
2. The visual factors would predict growth in each of the outcome variables from one wave of testing to a subsequent wave across all waves.
3. The predictive relationships would be stronger at the earlier waves.

Considering the spelling outcome, a significant concurrent, bidirectional relationship was found between spelling and CMD at wave one. No other concurrent relationships were supported. While this does not fully support the first hypothesis which anticipated significant relationships at each time point, it does provide some measure of support. It is also consistent with past literature that found a relationship between CMD and spelling in children whose ages fell within the range examined in this study (Cornelissen & Hansen, 1998; Boets et al., 2011). In addition to this, significant correlations were found between spelling at wave one and each of the later waves of both CMD and EVA. Taken together, these correlations show that there is a relationship between children’s spelling at the end of first grade and their visual processing abilities.

In terms of predictive links, EVA at wave one was found to significantly predict spelling performance at wave two, after controlling for past spelling ability. This lends some support to the second hypothesis. While falling short of what was hypothesized (predictive links across all waves), some predictive influence was found. This type of relationship in a longitudinal study begins to provide some evidence for a causal link, though it is insufficient to claim causality on this basis alone. This result also helps to extend some of the existing research on the subject. It had been hypothesized by researchers in the past that attentional processes may be an important factor when considering the relationship between visual processing and spelling (Cornelissen & Hansen, 1998). Additionally, while a relationship between endogenous visual attention and spelling was identified previously (Plaza & Cohen, 2007), research on EVA and spelling had proven more scarce. There had, however, been considerable research identifying links between reading and EVA (Franceschini et al., 2012; Vidyasagar, 2004; Hari et al., 2001). Reading research and spelling research often have a lot in common, and it would appear that the same commonality can be found here. Furthermore, this result is consistent with what might be expected considering the MD stream deficit theory given that the same area of the brain, the PPC, plays a significant role in both the MD pathway (Yantis, 2014) and EVA (Itti & Koch, 2001). This past research had implied that a relationship between EVA and spelling may exist. The results from the present study confirm this and take it a step further by showing that a predictive relationship is supported.

Turning to the orthographic knowledge outcome, again a significant concurrent, bidirectional relationship was identified between orthographic knowledge and CMD at wave one while other concurrent relationships were not supported, lending partial support to the first hypothesis. Prior research has identified that in Chinese adults, a significant relationship between CMD and orthographic processing exists (Qian et al., 2015). The present study expands upon this finding by demonstrating that the relationship exists in Canadian children as well. Significant correlations were also found between orthographic knowledge at wave one and all subsequent waves of CMD and EVA. These results are similar to the spelling outcome and again imply that the visual factors are highly associated with orthographic knowledge during earlier years, at the end of grade one.

Significant predictive links were found between CMD at wave two and orthographic knowledge at wave three as well as between EVA at wave two and orthographic knowledge at wave three. Although it does not confirm the second hypothesis in full, this does show that there is a predictive influence of both visual processing abilities on orthographic knowledge at a point in development. While slightly later than the other relationships observed thus far (beginning of grade two), the pattern of early influence is again seen here. Previous evidence for such a relationship was less abundant than for spelling. The study by Qian and colleagues (2015) mentioned above showed evidence of a link, and the relationship makes conceptual sense from an MD stream deficit viewpoint (Itti & Koch, 2001; Yantis, 2014; Qian et al., 2015; Kinsey, 2004). Now, with the addition of the results found in the present study, a predictive relationship has begun to be supported. Further research will be necessary to confirm this and to strengthen the support. An additional predictive link, that between CMD at wave four and orthographic knowledge at wave five, was approaching significance. Since this was only approaching significance, conclusions will not be drawn on the basis of this relationship. However, this may be an interesting topic for future research to investigate further.

Examining all of the results found in this study, certain patterns emerge. First, it is clear that visual processing abilities do have a predictive influence on spelling and orthographic processing. In addition, it appears as though this influence is limited to the earlier stages of this study, in grades one and two. This pattern supports the third hypothesis, that the effect of visual factors on spelling and orthographic knowledge would be stronger earlier on. Past research established a link between visual processes and spelling, but research on how it affects development has been severely lacking. A previous study by Plaza & Cohen (2007) found that it was in grade one that a different type of visual attention (endogenous) influenced spelling. This is consistent with the present study. By expanding upon that result, the current results provide valuable information on a potential factor that influences spelling development. Knowing that processes associated with the MD stream appear to affect children's spelling and orthographic knowledge at this early stage contributes to the depth of the MD stream deficit theory.

Given that letter-position encoding develops significantly during the years during which this study found MD stream processes influence spelling (Ktori & Pitchford, 2009) and given the expectation that letter-position encoding is the mechanism that links the visual and spelling processes (Kinsey, 2004; Cornelissen & Hansen, 1998), it stands to reason that during this same time period, the visual processes likely have a significant influence on letter-position encoding and letter-position encoding in turn likely has an influence on spelling at this stage. Letter order knowledge has a substantial influence both on the spelling task and the orthographic knowledge task in the present study, further lending support to this conclusion. Additional research will be necessary to confirm this association. Considering all of the above information, it would appear that it is at this early stage, in grades one and two, visual processes associated with the MD stream affect multiple distinct processes related to spelling.

A potential explanation as to why visual processes would have an influence on spelling early on, but not later has to do with experience. Simply by interacting with the world around them, children practice their visual abilities from infancy. Once they begin their schooling, they already have had substantial experience using their vision. Conversely, for many children, formal instruction in abilities related to language does not begin until they enter school. As such, it could be the case that in grades one and two as students are just beginning to learn to spell, their well-established visual processes have a greater influence on their spelling. Then, as children's knowledge of language and experience with written language increases, more linguistically based predictors that are well known in the literature (e.g., phonological awareness, rapid naming, reading ability) may have an even greater effect and replace the influence of visual processing. This interpretation is consistent with previous research that has found an influence of visual processing on spelling in grade one (Plaza & Cohen, 2007) and an influence of processes related to language (e.g., phonological awareness, rapid naming) on spelling later on, at the end of grade two (Plaza & Cohen, 2004).

There is some support in the literature for spelling interventions that target MD stream functioning (Lawton, 2011). If future research continues to support the use of visual processing training as a component of a literacy intervention, the timing of the predictive and concurrent relationships as identified in this study will have considerable implications regarding the timing of such an intervention. Developmental considerations are crucial to maximizing effectiveness of interventions. Future research into this subject may consider the difference in effectiveness of this type of intervention at different ages.

Limitations and Future Directions

The present study, being longitudinal in design, contributes to an ultimate goal of establishing a causal link between visual processing and both spelling and orthographic processing in childhood. However, the current results alone are not enough to make such a claim. To this end, replication of these results would be necessary. It would also be beneficial for future studies to consider a broader age range than that considered here. Additionally, a future study evaluating the effectiveness of training visual processes associated with the MD stream (e.g., CMD or EVA) in combination with spelling instruction as compared to spelling instruction alone would help to provide more conclusive evidence as to whether there is a causal relationship.

There is evidence in the literature that there may be a differing pattern of development in good spellers as compared to poor spellers on a number of different skills and abilities (Savage et al., 2005; Richards, Berninger, & Fayol, 2009; Treiman & Wolter, 2018). Given the number of participants in the present study and the statistical methods used, it was not possible to separate participants into good and poor speller groups. A future study that is able to examine how good and poor spellers differ in regards to when and how strongly visual processing variables have an influence on spelling ability would help to provide a more complete picture of the relationship.

The spelling literature shows that additional visual processing factors that were beyond the scope of this study may have an influence on children's spelling ability. One such factor is visual attention span, which is the amount of visual information that can be processed simultaneously. Some studies have shown that there is an association between visual attention span and spelling (van den Boer, van Bergen, & de Jong, 2015; Niolaki et al., 2020). Another possibility is endogenous visual attention which is often measured by visual search tasks (Plaza & Cohen, 2007; Liu, Chen, & Wang, 2016). Research has shown that associations between spelling and these visual factors do exist. Further longitudinal and intervention studies that consider these visual factors would help to broaden the general understanding of spelling development and the factors by which it is influenced.

In a similar vein, future studies would be prudent to examine the link between visual processing and letter position encoding over the time period addressed in the present study. Though the rationale of the MD stream deficit theory points to letter position encoding as a likely mechanism that connects the visual processing factors to the spelling factors (Cornelissen & Hansen, 1998; Kinsey, 2004; Ktori & Pitchford, 2009), it was not explicitly measured in this study. Letter position encoding could potentially be measured using a letter-string comparison task in which participants are shown a string of four letters (e.g., RTGM) then are shown another string that is either identical or has had the position of some of the letters altered and asked whether that string matches the first (Reilhac, Jucla, Iannuzzi, Valdois, & Démonet, 2012). Ideally, a future study on this topic would examine all of these variables (spelling, letter position encoding, and visual processes) over time in order to most accurately determine the relationship among them in relation to childhood development.

Conclusions

The results of the present study demonstrate evidence for concurrent and predictive links between visual processing abilities associated with the MD stream and both spelling and orthographic knowledge. This relationship appears to be focused in the early years, when children are in grades one and two. While this study contributes to the establishment of a causal influence of these visual processes on spelling and orthographic processing, further research is needed to confirm this. These results contribute to the wider understanding of spelling development and may have implications for future research and also potential interventions targeting children's spelling.

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Appendix A

Word-Likeness Judgement Task Items

1.	gree	pree	21.	wevf	filk
2.	miir	iigk	22.	tolz	tolb
3.	yyli	liyy	23.	eppi	dppc
4.	fdil	flid	24.	powl	lowp
5.	rool	rloo	25.	kuuj	jkuu
6.	hift	hifl	26.	wolg	wolt
7.	ullo	lluo	27.	geed	gaad
8.	lohh	olhh	28.	moke	moje
9.	wwfg	gwwf	29.	ossa	ovva
10.	noss	ross	30.	fant	tanf
11.	deff	devv	31.	miln	milg
12.	goot	gaat	32.	waaz	aazw
13.	wakk	kkwa	33.	toxh	togn
14.	jeet	eejt	34.	owwe	wweo
15.	vism	visn	35.	jofy	fojy
16.	milo	nlio	36.	udda	ddua
17.	dnif	drif	37.	pnad	plad
18.	gwup	gnup	38.	illo	ihho
19.	dlun	lund	39.	nilk	nilt
20.	imma	izza	40.	etti	elli

Appendix B

Additional Tables

Table 1
Demographics

		Frequency (Percent)
Sex		
	Male	94 (55.0%)
	Female	77 (45.0%)
SES		
	High	59 (34.5%)
	Middle	82 (48.0%)
	Low-Middle	13 (7.6%)
	Low	17 (9.9%)
First Language		
	English	154 (90.1%)
	Other	17 (9.9%)

Table 2
Latent Variable Indicator Summary

		Outcome 1		Outcome 2	
Latent Variable	Indicator	Coefficient	*p*	Coefficient	*p*
S_1	S1_1	0.844	< 0.001	-	-
	S2_1	0.853	< 0.001	-	-
S_2	S1_2	0.907	< 0.001	-	-
	S2_2	0.912	< 0.001	-	-
S_3	S1_3	0.892	< 0.001	-	-
	S2_3	0.918	< 0.001	-	-
S_4	S1_4	0.920	< 0.001	-	-
	S2_4	0.931	< 0.001	-	-
S_5	S1_5	0.941	< 0.001	-	-
	S2_5	0.931	< 0.001	-	-
OK_1	OK1_1	-	-	0.207	0.041
	OK2_1	-	-	0.556	< 0.001
OK_2	OK1_2	-	-	0.491	< 0.001
	OK2_2	-	-	0.867	< 0.001
OK_3	OK1_3	-	-	0.507	< 0.001
	OK2_3	-	-	0.593	< 0.001
OK_4	OK1_4	-	-	0.603	< 0.001
	OK2_4	-	-	0.791	< 0.001

OK_5	OK1_5	-	-	0.678	< 0.001
	OK2_5	-	-	0.734	< 0.001
CMD_1	CMD1_1	0.622	< 0.001	0.634	< 0.001
	CMD2_1	0.742	< 0.001	0.730	< 0.001
CMD_2	CMD1_2	0.807	< 0.001	0.809	< 0.001
	CMD2_2	0.841	< 0.001	0.840	< 0.001
	CMD3_2	0.694	< 0.001	0.687	< 0.001
CMD_3	CMD1_3	0.859	< 0.001	0.858	< 0.001
	CMD2_3	0.794	< 0.001	0.788	< 0.001
	CMD3_3	0.789	< 0.001	0.793	< 0.001
CMD_4	CMD1_4	0.741	< 0.001	0.737	< 0.001
	CMD2_4	0.844	< 0.001	0.839	< 0.001
	CMD3_4	0.803	< 0.001	0.804	< 0.001
CMD_5	CMD1_5	0.842	< 0.001	0.837	< 0.001
	CMD2_5	0.742	< 0.001	0.746	< 0.001
	CMD3_5	0.747	< 0.001	0.750	< 0.001
EVA_1	EVA1_1	0.856	< 0.001	0.811	< 0.001
	EVA2_1	0.793	< 0.001	0.835	< 0.001
EVA_2	EVA1_2	0.834	< 0.001	0.802	< 0.001
	EVA2_2	0.854	< 0.001	0.887	< 0.001
EVA_3	EVA1_3	0.859	< 0.001	0.852	< 0.001
	EVA2_3	0.818	< 0.001	0.826	< 0.001
EVA_4	EVA1_4	0.835	< 0.001	0.834	< 0.001
	EVA2_4	0.915	< 0.001	0.917	< 0.001
EVA_5	EVA1_5	0.840	< 0.001	0.826	< 0.001
	EVA2_5	0.779	< 0.001	0.793	< 0.001

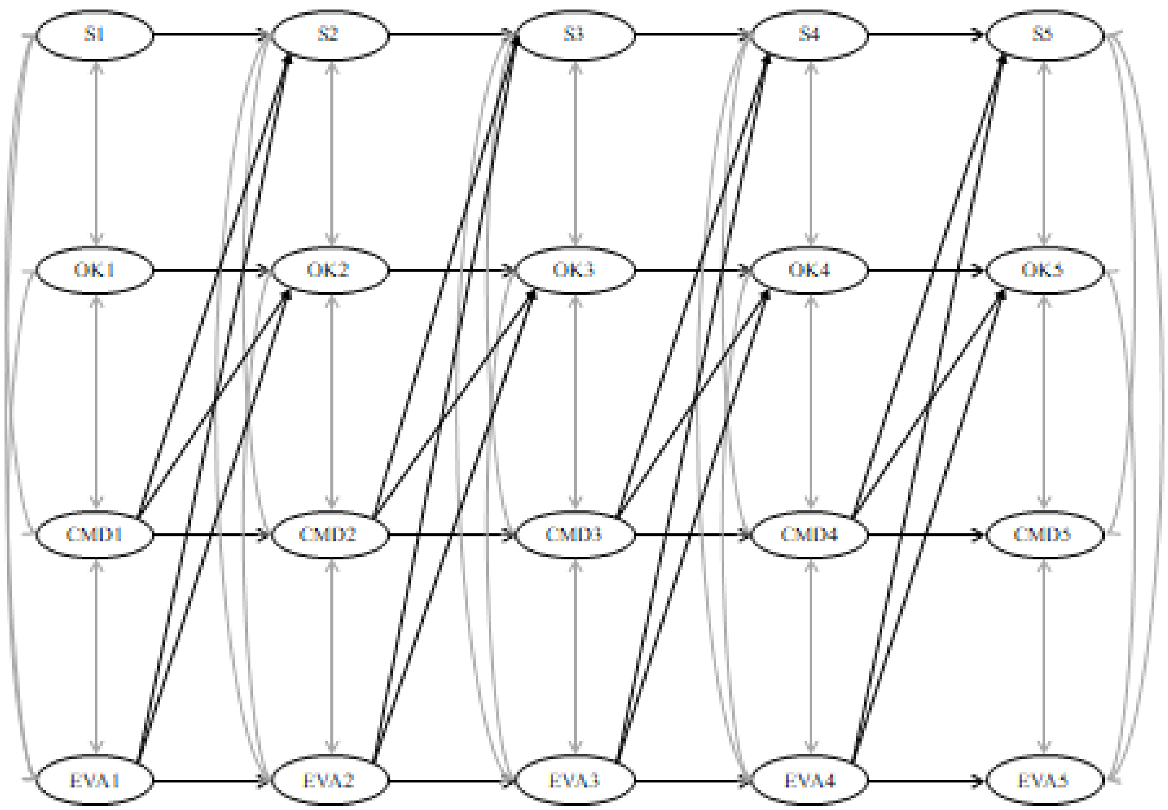
Note. S = Spelling total scores (1: odd-numbered items, 2: even-numbered items); OK = Orthographic Knowledge total scores (1: high orthographic and low phonological cuing items, 2: high orthographic and high phonological cuing items); CMD = Coherent Motion Detection percentage coherent-movement (1, 2, and 3 correspond to the order in which estimates were determined within a session); EVA = Exogenous Visual Attention, attention index scores (1: left-side cues, 2: right-side cues).

Appendix C

Additional Model Figures

Figure 1

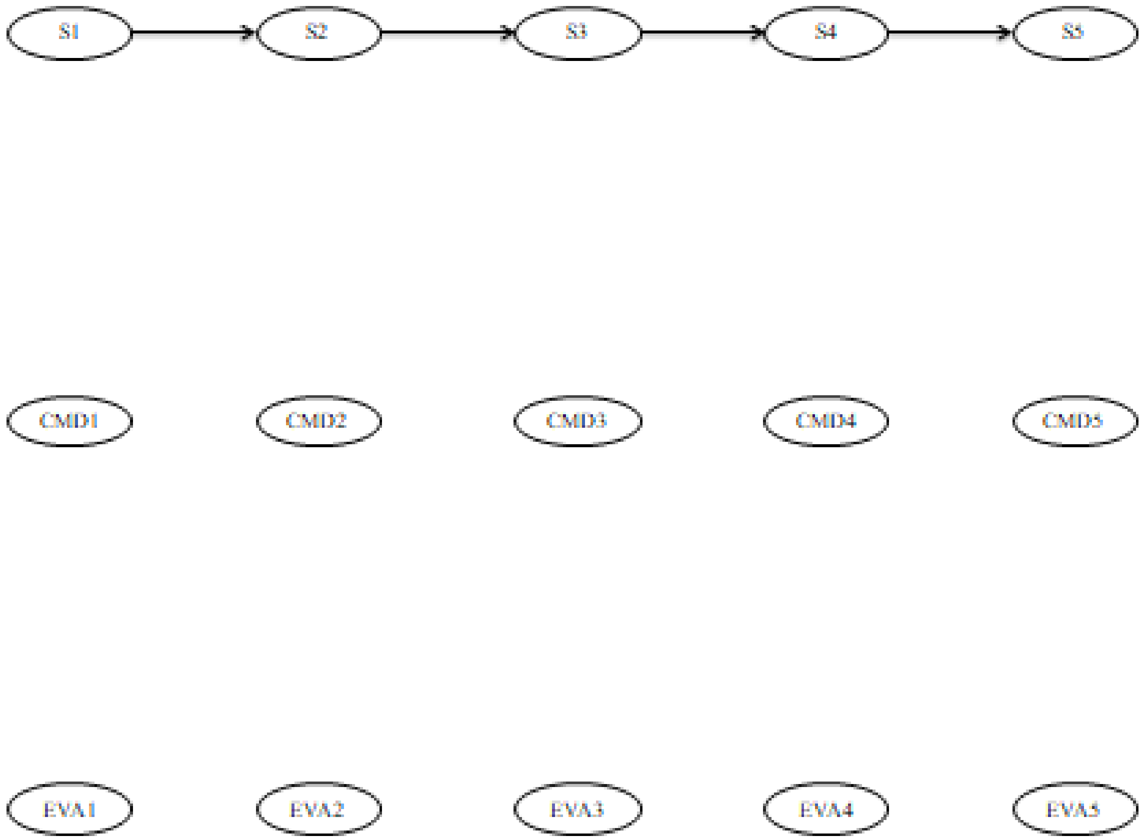
Fully Specified Model



Note. S = spelling, OK = orthographic knowledge, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to wave of testing. Unidirectional arrows indicate predictive links. Bidirectional arrows indicate correlations.

Figure 2

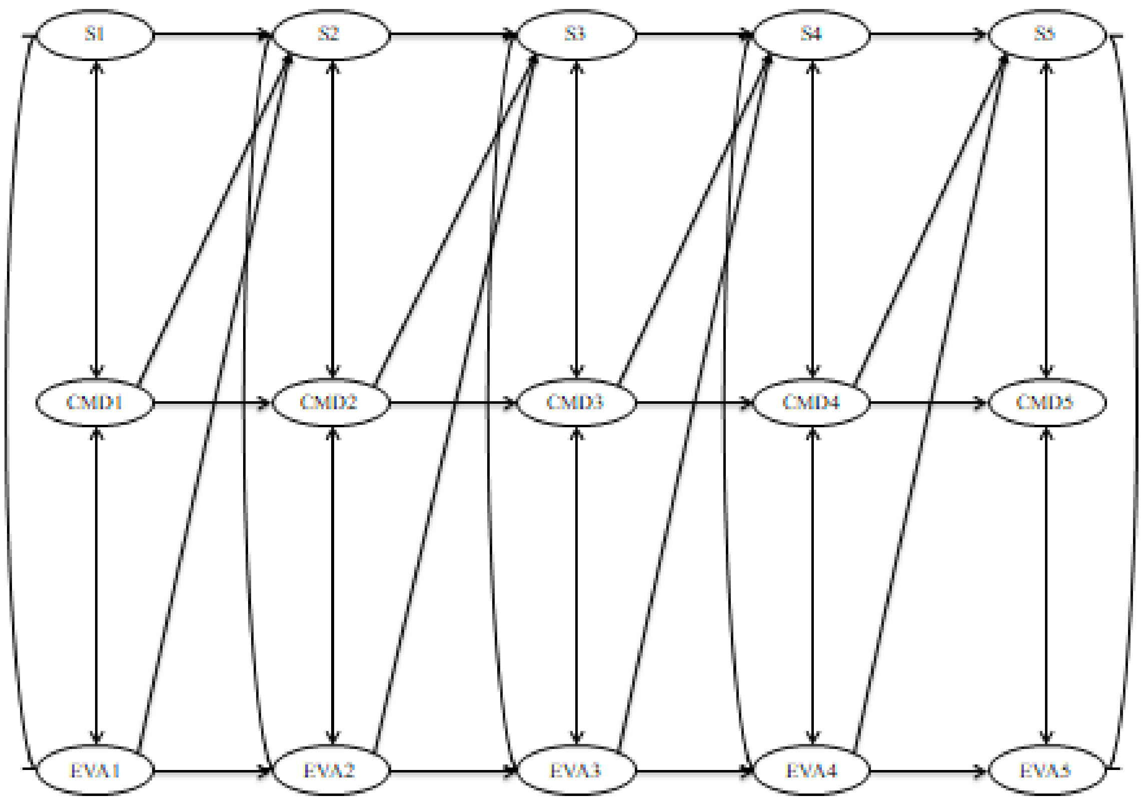
Outcome 1 Baseline Model



Note. S= spelling, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to the wave of testing. Variables were allowed to correlate freely; however, these correlations have been left out of the figure for the sake of clarity.

Figure 3

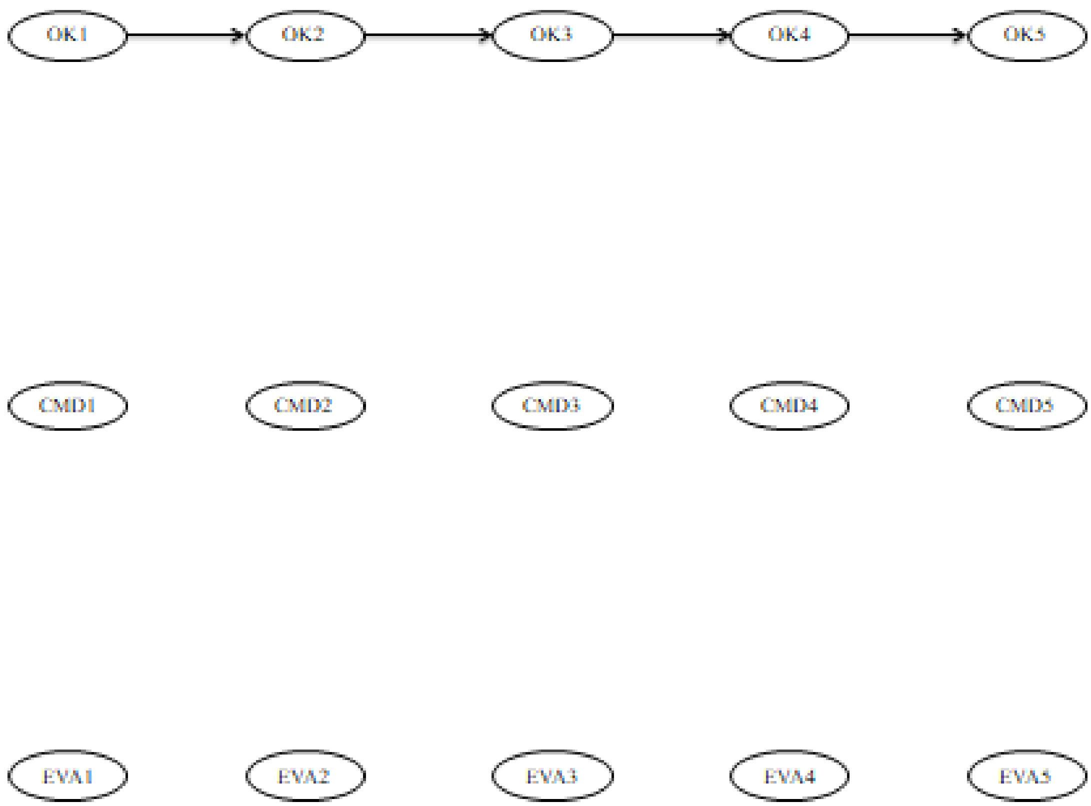
Outcome 1 Model 1



Note. S= spelling, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to wave of testing. Unidirectional arrows indicate predictive links. Bidirectional arrows indicate correlations.

Figure 5

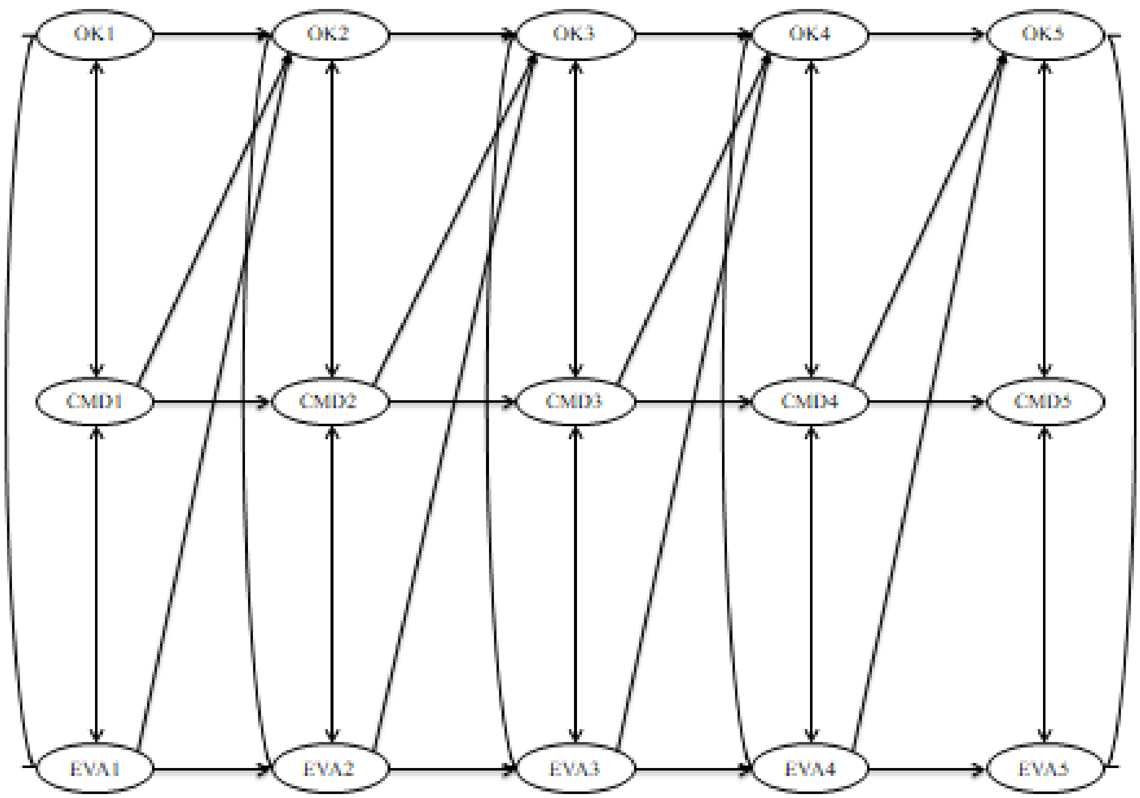
Outcome 2 Baseline Model



Note. OK = orthographic knowledge, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to the wave of testing. Variables were allowed to correlate freely; however, these correlations have been left out of the figure for the sake of clarity.

Figure 6

Outcome 2 Model 1



Note. OK = orthographic knowledge, CMD = coherent motion detection, EVA = exogenous visual attention. Numbers correspond to wave of testing. Unidirectional arrows indicate predictive links. Bidirectional arrows indicate correlations.