

MAGNOCELLULAR-DORSAL STREAM AND EXOGENOUS VISUAL ATTENTION

**Magnocellular-Dorsal Stream Functioning and Exogenous Visual Attention in Elementary  
School Readers: A Longitudinal Analysis**

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### Abstract

Reading difficulty is a common childhood phenomenon. Many children with reading difficulty experience a magnocellular-dorsal stream deficit. This deficit may impair exogenous visual attention (VA) by feeding anomalous information into the posterior parietal cortex, a part of the brain primary responsible for exogenous VA processes. Exogenous VA has an important influence on reading ability and is often impaired in children with reading difficulty. This longitudinal study was designed to illuminate the role of magnocellular-dorsal stream functioning and exogenous VA in reading difficulty, using data from 171 children with varied initial reading abilities tested throughout grades 1, 2, and 3 in public schools. A longitudinal structural equation modelling (SEM) design was utilized to examine the concurrent and predictive relationships of coherent motion detection performance (an index of magnocellular-dorsal stream functioning) and line motion illusion performance (an index of exogenous VA functioning) on reading decoding ability, respectively. The development of these relationships were also examined over time. The best fitting model showed evidence of persistent relationships between VA and early reading ability, and a predictive effect between exogenous VA at the earliest time point and subsequent reading performance. This implies that although VA influences reading growth only during early reading acquisition, reading decoding achievement at very early periods in development can have longer term influences on developing visual processes, emphasizing the importance of reading in the beginning stages. Results contribute to knowledge about the longitudinal associations between VA processes and reading ability and provide evidence for remediating VA difficulties in children with reading difficulty.

*Keywords:* Magnocellular-dorsal stream, posterior parietal cortex, coherent motion detection, exogenous visual attention, line motion illusion, reading difficulty

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## Magnocellular-Dorsal Stream Functioning and Exogenous Visual Attention in Elementary School Readers: A Longitudinal Analysis

Learning to read plays a central part in children's schooling and can significantly influence one's quality of life. Unfortunately, developmental dyslexia affects 5-10% of school age children (Sireteanu et al., 2005). As reading is a crucial part of children's education, occupational success and many activities of daily living, it is important to pinpoint the anomalies associated with reading difficulty. This can allow for earlier and effective prevention, screening, and intervention measures.

One of the processes that has been found to play an imperative role in reading acquisition, performance and development in addition to phonological awareness is visual attention (VA) (Vidyasagar & Pammer, 1999). The VA system encounters a large quantity of information while reading. In order to read effectively, one must be able to select and process appropriate information while ignoring and inhibiting irrelevant information. Specifically, VA is comprised of two main processes: a facilitatory process in the area in which one chooses to extract information, allowing for fast and precise processing, and an inhibitory process in the area in which one chooses not to select information, which suppresses irrelevant information (Facoetti et al., 2000).

Children with reading difficulty can experience a variety of VA problems (Tafti et al., 2014). The nature of these problems is not clear, but plenty of evidence supports the presence of an anomalous magnocellular-dorsal (MD) stream, a part of the brain responsible for coherent motion detection, as a primary deficit in dyslexia (Stein, 2018). According to Tulloch and Pammer (2018), "Growing evidence suggests that a deficit in the dorsal stream, specifically the visual pathway responsible for visuo-spatial attention, may be one of the areas most closely linked with reading development and reading delay" (p. 92). Additionally, it is believed that anomalous MD stream functioning often found in those with reading difficulty may further impair VA by feeding anomalous information into the posterior parietal cortex (PPC) (Posner & Petersen, 1990; Steinman et al., 1998). The PPC is an area with a strong anatomical connection to the MD stream and is responsible for various VA processes (Laycock et al., 2006; Facoetti et

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<sup>1</sup> For the remainder of this paper, *developmental dyslexia* will be used synonymously with *dyslexia*, *reading difficulty*, and *poor reader*. Although this study is using readers without a formal diagnosis of dyslexia, much of the research on reading difficulty has been done on individuals diagnosed with dyslexia.

al., 2000), a primary one being automatic VA, otherwise known as exogenous VA (Posner & Petersen, 1990). I will now discuss the nature of the MD stream and coherent motion detection, the PPC and exogenous VA, the connection between these, anomalies that exist in each among poor readers, and what is known about their development and relation to reading performance, respectively.

## **The Magnocellular-Dorsal Stream**

### ***The Nature of the Magnocellular-Dorsal Stream***

Anatomically, the magnocellular pathway begins in the retina and stems to the lateral geniculate nucleus (LGN) and primary visual cortex (V1), where it combines with parvocellular input before projecting to the middle temporal area (V5/MT) and the PPC (Merigan & Maunsell, 1993; Vidyasagar & Pammer, 1999). Although there is a fair bit of interaction between the magnocellular and parvocellular pathways, the ventral stream receives projections mainly from the parvocellular pathway (Hansen et al., 2001), whereas the dorsal stream obtains 90% of its input from magnocells (Kevan & Pammer, 2009; Stein, 2018). The ventral stream is primarily involved in object recognition, by processing information regarding the surface properties of objects like colour and shape (Hansen et al., 2001). On the other hand, the dorsal stream is involved in object localization, and processes information such as motion, depth, position, and location (Hansen et al., 2001). A primary role of the MD stream and the role I will be focusing on in this study is that of coherent motion detection. In the visual cortex, sensitivity for speed and direction of motion is present in the magnocellular neurons and processing stages to at least area V5/MT of the dorsal stream, which has neurons with large receptive fields. These neurons detect high temporal frequencies (D'Souza et al., 2011) and are well-suited for detecting motion in general, but specifically coherent motion, which requires one to combine motion signals spanning large areas (Skottun, 2015; Stein, 2001).

### ***Magnocellular-Dorsal Stream Deficits in Reading Difficulty***

Individuals with dyslexia have been found to experience impaired development of the magnocellular system, specifically, within the magnocellular layers of the LGN (Pammer et al., 2006). As evidence of this, Hansen et al. (2001) found a selective deficit in object localization but not object recognition among dyslexic adults, the former of which is controlled by the dorsal stream and the latter of which is controlled by the ventral stream. The researchers took this as evidence that the dorsal stream is especially susceptible to anomalies resulting from genetic



and/or developmental impairments (Hansen et al., 2001) because the dorsal stream happens to be more plastic in development in comparison to ventral stream (Englund & Palomares, 2012; Kassaliete et al., 2015).

Like any other reading-related deficit, many individuals with MD stream deficits learn to read just fine, and some individuals with reading difficulties do not possess MD stream deficits at all (Boets et al., 2011; Iles et al., 2000; Kassaliete et al., 2015; Stein, 2018; Wright et al., 2012). However, according to Stein (2018), evidence in support of MD stream deficits among individuals with dyslexia is immense. Namely, MD stream functioning reflected in coherent motion detection performance is often impaired in poor readers, with poor reading individuals exhibiting higher coherent motion detection thresholds than typical readers (Englund & Palomares, 2012; Hansen et al., 2001; Kassaliete et al., 2015; Kevan & Pammer, 2009; Wilmer et al., 2004).

#### ***Concurrent Relationships between the Magnocellular-Dorsal Stream and Reading***

Apart from the above-mentioned concurrent relationships between coherent motion detection thresholds and reading ability, there has also been intervention evidence showing a concurrent relationship between the MD stream and reading ability among children. Namely, there have been findings of improved coherent motion detection sensitivity and speed, as well as improved reading-related skills (reading speed, comprehension, fluency, phonological processing, and visual working memory) among grade 2 and 3 children with dyslexia directly following direction-discrimination training, thought to activate area V1/MT (Lawton, 2011; 2016; Lawton & Shelley-Tremblay, 2017). Similarly, some studies using slightly older dyslexic children have found improvements in not only coherent motion detection ability, but also in reading skills directly after interventions involving action video games, thought to improve the efficiency of the MD stream (Franceschini et al., 2015; Gori et al., 2016).

#### ***Predictive Relationships between the Magnocellular-Dorsal Stream and Reading***

There has also been evidence showing predictive relationships between the MD stream and reading ability among emerging readers. Specifically, coherent motion detection performance has been shown to predict future reading ability, with children who received a diagnosis of dyslexia in grade 3 exhibiting higher coherent motion detection thresholds than typical readers both in kindergarten at the pre-reading stage and in grade 1 (Boets et al., 2011). Similarly, children with a MD stream deficit in kindergarten have been found to exhibit reading

difficulties in grade 1 (Gori et al., 2016). These results provide evidence for earlier MD stream functioning predicting later reading ability.

### ***Reciprocal Relationships between the Magnocellular-Dorsal Stream and Reading***

**Theoretical Perspectives.** Although, it is important to consider that an anomalous MD stream may not necessarily cause poor reading; it may be a *result* of reading difficulty due to poor or insufficient reading experience and in turn less practice with MD stream skills (Goswami, 2015; Huettig et al., 2018; Olulade et al., 2013). This is a possibility, as lack of reading experience is commonly associated with dyslexia (Cunningham & Stanovich, 1997). Put another way, it is possible that improved MD stream sensitivity is a consequence, not a cause of emerging reading skills (Ramus, 2003; Talcott & Witton, 2002).

**Empirical Findings.** Good readers presumed to have similar reading experience as older readers with dyslexia (age-matched controls) show significantly better visual MD stream functioning and coherent motion detection performance than older readers with dyslexia (Laycock et al., 2006; Gori et al., 2016). Further, Joo et al. (2017) conducted a reading intervention using typical and dyslexic children aged 9. The researchers found that although reading scores improved post intervention, coherent motion detection sensitivity deficits remained stable. Furthermore, knowledge of letters in kindergarten does not have a predictive influence on coherent motion detection performance in grade 1 (Boets et al., 2011). These findings provide evidence against the reading experience hypothesis outlined above. Namely, they indicate that earlier reading ability does not predict later MD stream functioning, and in turn that there is no reciprocal relationship between the two.

### **Linking the Magnocellular-Dorsal Stream and the Posterior Parietal Cortex**

Despite the presence of coherent motion detection deficits in dyslexic individuals showing MD impairment, it is still unknown why impaired MD stream functioning influences literacy development (Boets et al., 2011; Skottun, 2015). Specifically, MD stream anomalies found in individuals with reading difficulty are typically quite mild and tend to occur in viewing conditions that are unusual for reading (Cornelissen et al., 1998; Facoetti et al., 2000). In turn, a theory that satisfactorily links MD stream deficits to anomalous reading development is lacking (Wright et al., 2012).

A plausible mechanism for how an impaired MD stream leads to impaired VA processes and in turn reading performance is through the PPC (Laycock et al., 2006). The PPC receives

primarily magnocellular pathway projections; if the magnocellular pathway is impaired, then it follows that PPC functioning may be impaired as well, due to anomalous magnocellular input to the PPC (Laycock et al., 2006). Namely, one would presume that those with MD stream deficits would not only perform poorly on tasks that depend upon the magnocellular system, but also on tasks in which the processes necessary for the task *originate* in the magnocellular system. That is, magnocellular deficits should be apparent later in visual processing (Iles et al., 2000).

### **Endogenous and Exogenous Visual Attention**

Before we discuss the PPC's role in VA, it is important to distinguish between the two primary types of VA, endogenous and exogenous. Endogenous VA is also known as top-down or voluntary VA, and exogenous VA is also known as bottom-up, involuntary, or automatic VA (Chica et al., 2013). Endogenous VA is utilized when an individual consciously allocates their VA to a certain area due to the expectation of a stimulus appearing in a specific spot or the need for purposeful visual search, for example (Chica et al., 2013; Wright et al., 2012). On the other hand, exogenous VA is used when some sort of salient stimulus captures VA, for example moving stimuli, luminance changes, or stimuli onsets. Here, the individual's VA is captured by the stimulus even though they have no intention of orienting their VA to that stimulus or location (Chica et al., 2013). Namely, in exogenous VA tasks, the target will often pop out pre-attentively, and target identification is typically easier and even automatic (Tulloch & Pammer, 2018).

### **The Posterior Parietal Cortex and Visual Attention**

The PPC is thought to play a key role in exogenous VA (Lellis et al., 2013), as well as in various VA processes often utilized in exogenous VA tasks (Lane, 2012; Posner & Petersen, 1990). These include but are not limited to: VA orienting (Facoetti et al., 2000; Hari et al., 2001; Posner & Petersen, 1990), resource distribution (Facoetti et al., 2000), VA shifting and eye movements (Boden & Giaschi, 2007; Iles et al., 2000; Lane, 2012; Steinman et al., 1998), VA focusing (Hari et al., 2001; Iles et al., 2000; Posner & Petersen, 1990; Vidyasagar, 2004; Vidyasagar & Pammer, 1999), and inhibition of irrelevant stimuli (Iles et al., 2000).

### ***Posterior Parietal Cortex Deficits in Reading Difficulty***

Abnormal MD functioning leading to faulty PPC input has been associated with various anomalous VA processes among poor readers that could interfere with performance on exogenous VA tasks. These include: anomalous VA orienting which reduces processing

efficiency (Vidyasagar & Pammer, 1999), difficulties inhibiting irrelevant stimuli (Iles et al., 2000; Moores et al., 2015; Posner, 1980; Tiadi et al., 2016; Wolf & Pfeiffer, 2014), slower VA shifting (Iles et al., 2000; Lewandowska, et al., 2014; Steinman et al., 1998; Vidyasagar, 2004; Vidyasagar & Pammer, 1999), slower VA capture, a prolonged attentional dwell time, impaired ability to focus VA, difficulty processing rapid stimuli sequences (Iles et al., 2000; Lewandowska et al., 2014; Tiadi et al., 2016), and difficulties modulating VA (Moores et al., 2015).

### ***The Nature of the Visual Attention Spotlight***

A VA concept that assumes control by the PPC, and that encompasses many of the VA abilities mentioned above, is known as the *visual attention (VA) spotlight*. The VA spotlight may represent a magnocellular-mediated feedback into area V1 to focus attention (Vidyasagar & Pammer, 1999). The VA spotlight plays a key role in disengaging, moving and engaging VA (Posner, 1980). The VA spotlight also identifies objects before one explicitly moves their eyes to the object's location, which allows for feature binding without noise from nearby objects (Triesman & Gelade, 1980; Triesman & Sfato, 1990). Further, the VA spotlight is especially important for exogenous VA processes and in turn tasks requiring exogenous VA, such as the line motion illusion (LMI) task (Banfi et al., 2017).

The primary role of the VA spotlight is to facilitate processing of relevant stimuli while inhibiting processing of irrelevant stimuli (Facoetti et al., 2000; Vidyasagar & Pammer, 1999). In order to do this, the VA spotlight consists of a small area of high visual acuity surrounded by a periphery of low visual acuity. This small beam of high visual acuity is oriented to and held on visual objects of interest (Lane, 2012). Specifically, the VA spotlight works to increase visibility of the attended location of interest by illuminating it, in turn enhancing visual processing (Posner & Cohen, 1984). Outside of the VA spotlight, visual stimuli are filtered out and visual processing is therefore suppressed (Steinman et al., 1998).

Furthermore, once attention is captured, the VA spotlight aids in attentional focusing, which is the process by which the width of the VA spotlight is adapted to the size of an object (Facoetti et al., 2000). In fact, one can make their VA spotlight either focused or diffused/distributed based on what needs to be processed. In the focused attention state, attentional resources are concentrated on a single area of interest. This allows for one to process information in one area of the perceptual field at a greater processing speed. Conversely, in the

distributed attention state, attentional resources are activated diffusely which allows the focus of attention to cover all possible areas in which the stimulus may appear. This allows one to process all the information in the perceptual field but at the cost of a lower processing speed (Facoetti et al., 2000; Ruffino et al., 2014).

### ***Visual Attention Spotlight Deficits in Reading Difficulty***

It follows that anomalous magnocellular input to the PPC can negatively affect one's ability to focus VA (Steinman et al., 1998; Vidyasagar 1999; 2004). In fact, both children and adults with reading difficulty have been found to experience issues modulating their attentional focus, and instead tend to display a distributed VA spotlight (Facoetti et al., 2000; Hildebrand & Kruk, 2019; Moores et al., 2015). This may lead to a distribution of VA resources that are diffuse within the focus of attention, like that outside of the focus of attention. In contrast, in typical readers, the attentional gradient becomes more diffuse as it progresses from the middle of the attentional focus to the periphery. This VA spotlight anomaly present in poor readers can contribute to an inability to selectively process specific areas of the visual field, with all perceived stimuli processed simultaneously (Facoetti et al., 2000). Additionally, there has been evidence for a narrower VA spotlight among children with developmental dyslexia, leading to VA orienting difficulties, specifically a right-over-left advantage, during exogenous spatial cueing tasks (Banfi et al., 2017; Facoetti et al., 2000; Facoetti et al., 2006; Steinman et al., 1998).

There is compelling evidence indicating the presence of an anomalous VA spotlight in dyslexic individuals, although the nature of this anomaly is unclear. Either way, it is apparent that the VA spotlight anomaly is a function of difficulty modulating the size of the VA spotlight. This can lead to inefficient processing of visual stimuli among individuals with reading difficulty; for example, through difficulties in using the VA spotlight to scan across letters and words while learning how to read (Buchholz & Davies, 2004).

### **The Magnocellular-Dorsal Stream, the Posterior Parietal Cortex and Reading**

In order to learn to read, children rely heavily on visual discipline (e.g., left-to-right scanning and visual-spatial organization) to identify letters and words (Plaza & Cohen, 2007). Specifically, learning to read requires certain eye movements and VA focus to encode the spatial position of and identify letters (Boets et al., 2011). The MD stream and the PPC both play a key role in these reading processes, namely letter/word recognition and spatial letter-position

encoding (Cornelissen et al., 1998; Cornelissen & Hansen, 1998; Husain, 1991; Laycock et al., 2006; Levy et al., 2010; Vidyasagar & Pammer, 2009).

The MD stream facilitates visual letter and word recognition by enabling the binding of stimulus features of letters and words (Pammer et al., 2006; Vidyasagar & Pammer, 2009), which reduces the need for the ventral system to select all regions of space (Pammer et al., 2006). The PPC then detects information regarding the form, shape, and spatial location of a word that is sent to it via the MD stream (Vidyasagar & Pammer, 2009), and transmits this information to the ventral stream where it is used to identify letters (Pammer et al., 2006; Vidyasagar, 2013). Additionally, during reading, it is believed that the VA spotlight is swept serially across the letters within a word. This process helps to recognize one element at a time and to ‘bind’ features together in order to recognize letters and encode their positions (Vidyasagar & Pammer, 2009).

Given the importance of the MD stream, PPC, and VA spotlight in letter recognition and spatial letter position encoding, and considering the anomalies present in these three aspects among poor readers as discussed above, it is unsurprising that children with dyslexia tend to have difficulties with both letter recognition and letter position encoding. Specifically, poor readers recognizing letters more slowly (Ozernov-Palchik et al., 2017) and take a longer time to sequence letters (Stein & Walsh, 1997) in comparison to typical readers. Difficulty modulating the size of the VA spotlight may be partly responsible for these difficulties in letter recognition and spatial letter position encoding. Specifically, difficulty sustaining the focus and modulating the size of the VA spotlight could interfere with processing relevant and inhibiting irrelevant letters and words when decoding text during reading (Facoetti et al., 2000; LaBerge & Brown, 1989). These deficits could lead to impaired reading performance by causing letters and words to appear crowded, displaced, or distorted (Atkinson, 1991 as cited in Lawton, 2016). It follows that among poor readers, processing stimuli simultaneously due to a diffuse VA spotlight results in the characteristics that comprise their reading: slow, effortful and inaccurate (Facoetti et al., 2000).

## **Growth and Development**

### ***Development of the Magnocellular-Dorsal Stream***

In order to better detect and remediate reading difficulty, it is important to examine the developmental trajectory of abilities pertinent to reading acquisition, such as those of the MD

stream and PPC. Looking at the development of these among both typical and poor readers and their relation to reading ability over time has the potential to provide important insight into factors that influence reading achievement and difficulty.

During typical development, the MD stream (as indicated by coherent dot motion detection tasks) has been found to gradually improve and fully mature by 10-12 years of age (Armstrong et al., 2009; Braddick et al., 2003; Crewther et al., 1996; ElleMBERG et al., 2003; Englund & Palomares, 2012; Gordon & McCulloh, 1999; Kassaliete et al., 2015). There has also been evidence for improved coherent motion detection performance among both typical and poor readers between the ages of 7 and 18, with coherent motion detection not reaching saturation until 18 years of age (Kassaliete et al., 2015). Finally, poor readers have been found to improve in coherent motion detection performance between kindergarten and grade 1 (Boets et al., 2011). These results provide evidence for similar coherent motion detection growth trajectories among both good and poor readers. Namely, that ability to detect coherent motion detection increases with age among both reader groups.

Along with general developmental trajectories of the MD stream, it is also important to consider when in development the MD stream exerts its strongest influence on reading performance. Giovagnoli et al. (2016) found evidence for more extensive and complex involvement of dorsal stream processes in both typical and dyslexic readers aged 8-10, as compared to typical and dyslexic readers aged 11-17. On the other hand, Younger et al. (2017) tested typical reading and dyslexic children aged 8-14 at one time point, and at another time point 2-3 years later, examining neural connectivity within the dorsal stream, and between the dorsal and ventral streams. Using fMRI, they found that when typical readers improved in their reading ability, they experienced more connectivity in the MD stream at first, followed by less connectivity in the MD stream as time went on. This decrease in MD stream connectivity was not interpreted as less reliance on the dorsal stream as reading develops, but rather, as higher efficiency of the dorsal stream all the while maintaining ventral stream connectivity. However, a much different pattern was found in the dyslexic sample: the MD stream functioning of these children was unchanged, and they did not sustain connectivity of their ventral stream. These results were interpreted to mean that only if one possesses strong MD stream functioning can decreases in it be attained without compromising ventral stream functioning and in turn reading ability (Younger et al., 2017). In turn, perhaps instead of there being a “critical period” in

development during which the MD stream is most utilized in reading among typical and dyslexic readers as was found by Giovagnoli et al. (2016), there actually exists a time when the MD stream becomes more efficient, which is only experienced by typical readers (Younger et al., 2017). In turn, I believe that research using younger children (such as this study) is needed to provide further insight into when MD stream functioning is most important in reading development.

### *Development of Exogenous Visual Attention*

Plenty of literature indicates that the most basic exogenous VA processes develop earlier than endogenous VA, with the ability to shift VA to exogenous cues reaching adult-like levels shortly after birth (Iarocci & Burnack, 2004; Johnson et al., 1991; MacPhearson et al., 2003; McDermott et al., 2007; Valenza et al., 1994). Specifically, areas of the PPC responsible for exogenous VA reach almost full maturity by 6 months of age (Ristic & Kingstone, 2009). In turn, there has not been a significant difference found between children and adult performance on certain exogenous VA tasks (Ristic & Kingstone, 2009; Rueda et al., 2004; Hommel et al., 2004).

However, more-specialized exogenous VA abilities, as well as VA abilities that could interfere with performance on exogenous VA tasks as discussed previously tend to start off immature and improve with age. In terms of more-specialized exogenous VA abilities, Lellis et al. (2013) conducted a study examining the performance of 6-10-year-old children on an exogenous VA cueing task. Younger children were found to have slower reaction times than older children (Lellis et al., 2013). This was taken as evidence that exogenous VA processes depend on nervous system maturation with increasing age during childhood (Lellis et al., 2013).

In terms of VA abilities that could interfere with performance on exogenous VA tasks, young children have been found to experience immature, coarser-grained attention resolution, leading to attention being “spilled over” to surrounding objects and in turn limiting the precision and accuracy of VA deployment in exogenous VA tasks (Wolf & Pfeiffer, 2014). Specifically, the extent to which individuals can deploy fine-grained attention resolution tends to increase between the ages of 7 and 11, and age 13 and adulthood (Wolf & Pfeiffer, 2014). Along the same lines, there is also evidence for immature exogenous VA functions as indexed by weaker inhibition capabilities among younger children (Bunge et al., 2002). Namely, as children age, their inhibition skills increase and vulnerability to distracting stimuli decrease (McDermott et al.,



2007). In turn, younger children may be more susceptible to having their exogenous VA activated by distracting stimuli.

These findings make intuitive sense when considering the processes involved in learning how to read. When learning to read, the VA spotlight must move sequentially over letters and words from left-to-right at a fine enough spatial resolution to perceive them properly. It is thought that the nervous system must learn this attentional scanning ability, as innate visual search processes do not naturally work in this way (Vidyasagar & Pammer, 1999; Lane, 2012). Rather, the VA spotlight randomly (not systematically) spans the visual field (Horowitz & Wolfe, 1998 as cited in Vidyasagar & Pammer, 2009). In turn, we can assume that with age and in turn increased experience and practice with reading, this function gets better (Vidyasagar & Pammer, 1999). Finally, it is important to note that unlike the literature presented on the development of the MD stream, these studies did not examine the development of exogenous VA in good versus poor readers. As there have been findings for improved MD stream functioning that is similar among typical and poor readers (Boets et al., 2011; Giovagnoli et al., 2016; Kassaliete et al., 2015), especially in early elementary school-aged children (Younger et al., 2017), it is possible that exogenous VA development will operate similarly.

## **The Present Study**

### ***Related Findings***

To my knowledge, only one study thus far has examined the relationship between MD functioning and VA among children with and without dyslexia, although this study focused solely on endogenous VA and used only one age group (Wright et al., 2012). The researchers found that dyslexic children with impaired coherent motion detection did not exhibit impaired endogenous VA in comparison to dyslexic children with intact coherent motion detection and asserted that MD and visual-spatial attention difficulties were unrelated (Wright et al., 2012). I believe this conclusion to be both premature and too broad, as only one age group was examined, and solely endogenous VA was examined. Namely, the relationships between MD stream functioning and VA can change over time. Further, it is important to examine exogenous VA specifically due to the strong link between the MD stream and the PPC (Laycock et al., 2006), the latter of which is primarily responsible for exogenous VA processes as discussed above.

The one study I am aware of that has examined the relationship between MD functioning and exogenous VA used adults. Using endogenous and exogenous visual search tasks, this study

found that dyslexic adults with impaired coherent motion detection exhibited impaired endogenous, but not exogenous, VA in comparison to dyslexic adults with intact coherent motion detection (Iles et al., 2000). In turn, research is needed to identify whether this is also the case among children. Namely, as previously discussed, although exogenous VA is at adult levels early in life, other more-subtle aspects of VA that can impact exogenous VA, like the VA spotlight, are still developing, and these developmental differences could be enough to bring about differences between child and adult patterns. Research is also needed to identify whether this relationship holds up when using a type of exogenous VA task that is different from the one used by Iles et al. (2000). Namely, their exogenous VA task was a basic visual search task that required subjects to simply click a mouse whenever any visual stimulus appeared on the computer monitor. As will be discussed in detail below, the LMI task has the potential to detect more nuanced and specialized aspects of exogenous VA than Iles et al.'s task did, and in turn may act as a better gauge of exogenous VA ability.

### ***Rationale***

To summarize, the literature presented throughout this thesis reflects findings pertaining to the concurrent and predictive relationships between MD stream functioning, exogenous VA and reading. However, literature examining these three factors together longitudinally in children is lacking. In turn, this study examined the nature of these relationships in order to shed light on how they manifest over time among early-years readers. Specifically, I explored: to what extent the MD stream and exogenous VA relate to reading ability concurrently, and to what extent the MD stream and exogenous VA uniquely predict growth in later reading ability.

Looking at these relationships can bring light to whether VA deficits often seen in reading difficulty are specific to lower-level MD stream deficits, or also extend to higher-level visual functions in the PPC, specifically exogenous PPC functions receiving their input from the MD stream (Iles et al., 2000). Considering this strong link between the MD stream and the PPC (Laycock et al., 2006), and the exogenous VA anomalies often present among poor readers outlined in previous sections, research on how the MD stream interacts with exogenous VA to affect reading ability over time could uncover new influences not revealed by previous studies. Namely, as it is possible that an anomalous MD stream may lead to inconsistent VA improvement over time or failure to improve in general (Tulloch & Pammer, 2018), it is important to consider the potential intermediate step of exogenous VA between MD functioning

and reading, and to assess this relationship longitudinally. Doing so can help identify how robust these exogenous VA anomalies are in poor readers (Kevan & Pammer, 2009). Phrased another way: there is an established MD stream dysfunction in dyslexic children (Stein, 2018); there is a strong anatomical link between the MD stream and the PPC (Laycock et al., 2006); the PPC is responsible for exogenous VA (Posner & Petersen, 1990); exogenous VA processes are important for reading performance (Vidyasagar & Pammer, 2009). In turn, impaired MD stream functioning should contribute to impaired exogenous VA, which should then lead to impaired reading. This relationship should maintain across the early years of reading acquisition (Banfi et al., 2017; Facoetti et al., 2000; Facoetti et al., 2006; Stein, 2018). This study took all these potential relationships into consideration, which shed light on the interrelated nature the MD stream, exogenous VA, and reading ability.

Finally, it is important to note that the literature reviewed above suggests that concurrent and predictive relationships between MD stream functioning and reading ability, and between exogenous VA and reading ability, as well as the development of the MD stream and exogenous VA hold irrespective of one's reading ability. In turn, this study used the sample as a complete, "unselected" set, without separating good and poor initial readers.

### *Hypotheses*

Based on the above literature review, several hypotheses about the nature of MD stream and PPC functioning in reading among early-elementary years children were developed. These hypotheses are based on the assumption that good and poor reading abilities constitute a continuum of skill in the same population. My first hypothesis centers on growth in abilities across time:

1. Coherent motion detection, LMI, and reading decoding performance should improve in children over time, indicating general development of the MD stream (Armstrong, et al., 2009; Boets et al., 2011; Braddick et al., 2003; Crewther et al., 1996; ElleMBERG et al., 2003; Englund & Palomeres, 2012; Gordon & McCulloh, 1999; Kassaliete et al., 2015), exogenous VA (Lellis et al., 2013; McDermott et al., 2007; Vidyasagar & Pammer, 1999; Wolf & Pfeiffer, 2014) and reading ability.

My second group of hypotheses centers on concurrent relationships between MD stream functioning, exogenous VA and reading decoding:

1. MD stream functioning, as indexed by coherent motion detection performance on a random dot kinematogram (RDK) task (Wright et al., 2012), will be significantly related to reading decoding concurrently at each time point. This expectation is based on the involvement of the MD stream in letter recognition and letter position encoding (Pammer et al., 2006; Vidyasagar & Pammer, 2009).
2. PPC functioning, as indexed by exogenous VA/VA spotlight performance on a LMI task (Hari et al., 2001), will be significantly related to reading decoding concurrently at each time point (Banfi et al., 2017; Facoetti et al., 2000; Facoetti et al., 2006). This expectation is based on the involvement of exogenous VA and the VA spotlight in letter recognition and letter position encoding (Vidyasagar & Pammer, 2009; Vidyasagar Pammer, 2009; Vidyasagar, 2013).

My third group of hypotheses centers on predictive relationships between MD stream functioning, exogenous VA and reading decoding:

1. Predictive relationships between MD stream functioning and reading decoding should be observed throughout grades 1-3 (Englund & Palomares, 2012; Franceschini et al., 2015; Gori et al., 2016; Kassaliete et al., 2015; Kevan & Pammer, 2009; Lawton 2011; 2016; Lawton & Shelley-Tremblay, 2017; Wilmer et al., 2004), with earlier MD stream functioning predicting later reading decoding performance (Boets et al., 2011; Gori et al., 2016).
2. I expect the same predictive relationships between exogenous VA ability and reading decoding as I expect between MD stream functioning and reading decoding outlined above. Namely, I expect a predictive relationship between exogenous VA and reading decoding for all readers throughout grades 1-3, with earlier exogenous VA functioning predicting later reading decoding performance.
3. Although I expect the above predictive relationships to be present throughout all time points, I expect them to be stronger earlier in development, when VA processes may exert the strongest influence on reading decoding as children are just beginning to learn how to decode letters and words (Younger et al., 2017; Cornelissen et al., 1998; Cornelissen & Hansen, 1998; Husain, 1991; Laycock et al., 2006; Levy et al., 2010; Vidyasagar & Pammer, 2009).

To test these hypotheses, I used data from an existing database on children who completed the RDK and LMI tasks, as well as tasks measuring reading decoding ability. Testing took place during five occasions across two and a half years, with testing occurring approximately every six months, starting in the middle of grade 1. Details are discussed in the following section.

## **Methods**

### **Participants**

Participants were 171 grade 1 students from 12 Winnipeg schools within 3 School Divisions. 94 children were male and 77 were female. Children took part in five waves of testing, 6 months apart, from the second half of grade 1 to the end of grade 3. At the end of testing, 137 children remained. Children's ages spanned from 5 to 8 years old throughout the study. At-risk and typical readers were selected based on classroom teacher nominations prior to the first testing occasion. All children had normal or corrected vision.

### **Procedure**

The time at which the first participant began the study was considered Time 1. Time was measured as progressing by months from this point onwards. Each of the five testing occasions involved six half-hour sessions. The tasks were distributed among these sessions in order to reduce children's fatigue. The order in which the tasks were presented to the children varied slightly, but generally the children were presented first with the pencil-paper tasks, followed by the computer-based tasks. Tasks were administered in the children's schools by a research assistant and volunteer undergraduate psychology and honours students from the University of Manitoba. The researchers were trained on the measures and were unaware during testing of the reader group membership of any of the participants.

### **Apparatus**

The computer tasks used to measure VA were created using Vpixx version 2.5 software (VPixx, 2001). The tasks were displayed on a 17" Sony LCD monitor with a refresh rate of 60 HZ, display resolution of 1250X1024 pixels, and pixel response time of 16 ms (Kruk & Luther Ruban, 2018). The monitor was connected to a Macintosh G4 Power Book laptop with a: 500:1 contrast, display resolution of 0.264 mm pixels, and pixel response time of 16 ms. The screen had a matte, black, light-proof cardboard viewing box that was 57 cm long attached to it to ensure that factors such as the distance the child was looking at the screen from and lighting conditions remained stable throughout testing (Kruk & Luther Ruban, 2018).

## Measures of Visual Processing

### *Random Dot Kinematogram*

The RDK task (Cornelissen & Hansen, 1998; Raymond & Sorensen, 1998) is the method traditionally used to assess MD stream functioning by measuring coherent motion detection sensitivity (Wright et al., 2012). It is suited towards this purpose because it consists of rapidly moving, low-luminance, white stimuli (Demb et al., 1998; Purpura et al., 1988; Steinman et al., 1998).

The RDK was administered twice during Wave 1 to reduce children's fatigue, and 3 times during each successive wave of testing. The task began with four practice trials in which all dots were moving in the same direction. In order to progress to the next set of practice trials, children needed to get all four trials correct. This was followed by eight practice trials where 90% of the dots were moving in the same direction. In order to progress to the test trials, children had to get at least six of these trials correct and were given three chances to do this. If they were unable to do this, the task was stopped, and they were retested another day.

The test trials involved the presentation of a fixation cross followed by 150 white signal and noise dots, each having a diameter of 2.5 minutes of arc. The dots appeared in a black, 3° square. This square was surrounded by a larger square measuring 7.4 x 7.4 visual degrees. The luminance level was set at the maximum level for the dots and at the minimum level for the background. Each dot was presented for 64ms (equal to 4 frames) before it would disappear and be replaced with another dot appearing elsewhere on the screen. The dot display appeared on the screen 250ms from trial onset and remained for 320ms (equal to 20 frames).

The dots moved at a velocity of 11 deg/s. The signal dots appeared to move in an upwards or downwards linear fashion, whereas the noise dots appeared to move randomly across successively presented frames (Wright et al., 2012). Participants were asked to state the way they believed the dots were moving. The percentage of signal dots required for the participant to recognize the direction of coherent motion correctly 75% of the time was considered their coherent motion detection threshold. Meaning, higher scores indicated poorer performance. Children who could not achieve 75% accuracy even with 100% dot coherence were assumed to require 100% dot coherence to be able to detect coherent motion. Coherent motion detection threshold was calculated using the parameter estimation by sequential testing (PEST) technique. The program determined the percentage of dot coherence for each trial based on answers given

on previous trials. After each trial, the program calculated the coherent motion detection threshold for that trial and produced a confidence interval. The trials stopped once the program had reached a 95% confidence interval, or until the child completed 100 trials. Reliability for the RDK task was .63 (Kruk & Luther Ruban, 2018).

### ***Line Motion Illusion***

The illusion that occurs in the LMI task (Hari et al., 2001) is thought to reflect more rapid processing of stimuli presented in attended locations thanks to attention capture by the display of an attentional cue (Hikosaka et al., 1993). Hence, the LMI task is a measure the strength of exogenous VA capture to visual cues (Hari et al., 2001; Steinman et al., 1997) as well as VA spotlight functioning (Steinman et al., 1998; Hikosaka et al., 1993). Namely, during spatial (exogenous) cueing, children's visual attention is captured and directed to the target location, and children's VA spotlight is adjusted accordingly (Albonico et al., 2016). Atypical cueing performance, indicated by less-frequent reporting of the experience of the illusion, would in turn indicate that the attentional filtering system is not working efficiently, which would imply that the VA spotlight is either too broad or too narrow (Banfi et al., 2017). In fact, individuals with reading difficulty exhibit a diminished cueing effect on the LMI task (less-frequent experience of the illusion) compared to those without reading difficulty (Hari et al., 2001).

The LMI task was administered over four separate sessions. The LMI task began with four practice trials. In these trials a longer delay was used between the onset of the cue and the presentation of the line compared to the test trials. In turn, for these trials the illusion was artificially created with a line-motion animation to make sure the participants comprehended the instructions. Namely, the line was intentionally created to appear as if it were growing from the cued box to the box horizontal from it. To move onto the next set of practice trials, children had to get all four trials correct. In the next eight practice trials, the same procedure was followed but with a shorter delay. To progress to the test trials, the children needed to get at least six of these trials correct and were given three chances to do this. If they were unable to achieve this level of performance, the task was stopped, and they were retested another day.

The general process of the LMI task involves a fixation point appearing. Then, two boxes appear slightly above and two boxes appear slightly below the fixation point on the left and right sides. Following a short time delay, one of the four boxes is cued in one of two ways; that is, either the luminance level of one of the boxes increases momentarily, or a boarder appears

around it. Following this cue, a line appears connecting the two boxes. The line then disappears after presentation. The illusory line motion effect occurs when the participant perceives the line as growing away from the cued box, towards the opposite-side box (Chica et al., 2013). If the cue is not present, the illusion does not occur. During the test trials, children were told that they would see a line “growing” in between the bottom or top two boxes. Children then indicated the way the line appeared to be moving by pointing (Kruk & Luther Reuban, 2018).

There were two separate conditions of the LMI task: the contrasted-defined condition (LMI-C) and the isoluminant condition (LMI-I). Within these two conditions, there were no-cue conditions and cued conditions. The LMI-C condition consisted of low-luminance, white stimuli presented on a black background and was used to maximize magnocellular system activity (Demb et al., 1998; Purpura et al., 1988; Steinman et al., 1997). The background and stimuli had luminance levels of 2.0 cd/m<sup>2</sup> and 7.9 cd/m<sup>2</sup>, respectively. On the other hand, the LMI-I condition consists of conditions that are used to maximize parvocellular system activity, with cuing occurring based on changing the colour but not luminance of the cue. As this study focuses solely on MD stream functioning, the LMI-C condition is the only condition that was included in this analyses. The LMI-C condition consisted of 96 trials: 64 cued, 12 without a cue, and 20 distractors. Of the 64 cued conditions, half involved a cued box above the fixation point, and half involved a cued box below the fixation point.

**Cued Condition.** The cued LMI condition consisted of a fixation point in the center of the screen presented for 256 ms, surrounded by 4 boxes (cue locations) presented in each corner (periphery) of the screen in the left or right visual field, for 495 ms. The boxes had a frame width of 1° of visual angle and were located at a visual angle of 3.9° from the center fixation. One of the boxes became the cue when either of two things occurred: the luminance increased to 18.79 cd/m<sup>2</sup>, or a boarder appeared around it for 48 ms at a luminance of 18.79 cd/m<sup>2</sup>. After the box was cued, a line with a width of 0.4° of visual angle appeared between the two upper or two lower boxes at different stimulus onset asynchronies (SOAs). SOAs were either 0 ms, 16 ms, 32 ms, 48ms or 64 ms. After 48 ms, the line and all the stimuli disappeared.

When the line and the cue are simultaneously presented at a 0 ms SOA, a weak or no illusion should be experienced, and answers are expected to be chance reports of leftward and rightward perceived motion. Conversely, at a 64 ms SOA, a very strong illusion is experienced, and answers are therefore expected to be correct 100% of the time. In turn, the highest and



lowest SOAs were present during only four trials per session, whereas the remaining three SOAs were present in eight trials per session.

**No-Cue Condition.** The no cue condition acted as a control condition. It consisted of parameters like that of the cued condition, just without the presence of the cue. Here, answers are expected to be chance reports of leftward and rightward line directions.

**Apparent Motion Condition.** The apparent motion condition acted as a second control condition and was used to prevent the participants from responding in a manner that assumed the line would always grow away from the cue (Cribb-Lokhorst, 2008; Steinman et al., 1997). Specifically, the line was animated to appear as if it were growing toward the cue; the direction opposite to that which would be expected if the illusion were taking place.

LMI scores, proportion of responses for line motion in the direction away from the cue, were calculated for each participant at each wave for the LMI-C cue condition when the cue occurred on each of the left and right sides. Specifically, four outcome variables were created for each participant at each wave for the LMI task: LMI-C – left side cue and LMI-C – right side cue for above and below fixation, respectively. Attention index scores were also calculated. These were based on proportion of reported line direction expected in a given LMI-C cue location condition in comparison to proportion of reported line direction expected in a given apparent (animated) motion condition. This was done to control for the presence of any biases associated with inattention or misunderstanding of the task (Steinman et al., 1997). The proportion of rightward animated line motion in the apparent motion trials (for the 10 above- and 10 below-fixation right-cue trials averaged separately) was subtracted from the proportion of (expected) rightward line motion in the left-cue trials across SOAs (16 above-fixation, and 16 below-fixation trials averaged separately). The same process was followed for leftward motion; the proportion of leftward animated line motion in the apparent motion trial (for the 10 above- and 10 below-fixation left-cue trials averaged separately) was subtracted from the proportion of (expected) leftward line motion in the right-cue trials across SOAs (16 above-fixation, and 16 below-fixation trials averaged separately). Finally, an average, for each of the left- and right-cue conditions was calculated by averaging the corresponding above-and below- fixation condition AI scores, to yield 2 AI scores per wave: left-LMI-cue (above-and -below-fixation), and right-LMI-cue (above-and -below-fixation). Positive AI scores are associated with accelerated visual processing speed in attention capture, which is an index of exogenous attention, whereas

negative AI scores are associated with decelerated (slowed) visual processing speed in attention capture. A higher positive AI score indicates a stronger experience of the illusion (Steinman et al., 1997).

### **Reading and Reading Control Measures**

For each task, items increased in difficulty as the task progressed. The total number of items correct was the measure used. Incorrect responses received a score of zero and correct responses received a score of one. The raw scores, used in the modeling analyses to test for the second and third set of hypotheses, were the number of correct item responses.

### ***Wechsler Abbreviated Scale of Intelligence***

The Matrix Reasoning and Vocabulary subtests of the WASI were used to measure intelligence (Wechsler, 1999). On the Matrix Reasoning task, children were shown a series of drawings of incomplete objects and were required to choose which of five options they believed fit the missing space. On the Vocabulary task, children were asked to define a series of words presented visually and orally. Both tasks ceased after three consecutive incorrect responses. The total score for each task was the number of accurate responses. The WASI subtests were used to ensure children had the capacity to understand the directions of the tasks, assumed to be partially a function of IQ. An estimated IQ score was derived using a composite score of the Matrix Reasoning and Vocabulary subtests. For this purpose, a cutoff score of 75 was used (American Psychiatric Association, 2013).

### ***Comprehensive Test of Phonological Processing***

To measure phonological awareness, the elision subtest from the Comprehensive Test of Phonological Processing (Wagner et al., 1999) was used. This standardized measure was based on the outcome scores from the first wave of testing. The elision subtest contains 20 test items and is used to measure one's ability to remove specified morphemes or phonemes from orally presented words. In the practice trials children were told to repeat a word after the researcher, and then to say the word back again with an indicated morpheme removed (e.g., "Say 'baseball'. Now say 'baseball' without saying without saying 'ball'"). If the child was able to successfully do this on at least one out of three practice trials, the test trials began. In the test trials children were instructed to repeat a word after the researcher, and then to say the word back again with an indicated phoneme removed (e.g., "Say 'fish'. Now say 'fish' without saying without saying

/f/"). The test continued until all items were completed or until the child provided 3 incorrect responses in a row (Wagner et al., 1999).

### ***Decoding***

A planned latent factor, indicating reading decoding was created by combining scores on 2 subtests: The Reading subtest of the Wide Range Achievement Test, 3<sup>rd</sup> Edition (WRAT-3; Wilkinson, 1993) and the Word Identification subtest of the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1998). Raw scores on each subtest were averaged for each participant.

**WRAT-3 Reading.** The WRAT-3 Reading subtest consists of 57 test items and is used to measure letter and word recognition and naming, i.e., letter and word decoding ability. Children were instructed to name fifteen letters of the alphabet. They were then asked to name forty-two words. Children were allowed 10 seconds to respond to each item. The test continued until all items were completed or until the child provided 10 incorrect responses in a row (Wilkinson, 1993). Standardized alpha reliability for the WRAT-3 Reading subtest based on the normative sample was 0.95 (Wilkinson, 1993).

**WRMT-R Word Identification.** The WRMT-R Word Identification subtest consists of 106 test items and is used to measure word decoding ability of both regularly and irregularly spelled words. Children were instructed to read increasingly complex words out loud. The test continued until all items were completed or until the child provided 6 incorrect responses in a row (Woodcock, 1998). Split-half reliability for the WRMT-R Word Identification subtest based on the normative sample was 0.98 (Woodcock, 1998).

## **Data Analysis**

### **Data Analysis Overview**

Statistical analyses were performed using IBM SPSS Statistics version 27, and Mplus, version 8.5. First, descriptive statistics for all measures were examined. Next, a missing data analysis was performed to identify the presence of any systematic differences on key measures between those with and without complete data, to identify if data was missing at random (MAR) or not missing at random (NMAR) (Enders, 2010). The main reason for missing data was that children moved to different schools (and so were not available for subsequent testing occasions), or children were ill on the day of data collection. T-tests did not identify the presence of systematic differences between missing data and non-missing data groups. Thus, it could be

concluded that data was MAR. However, as discussed below in the results section, t-tests identified the presence of systematic differences at baseline between attrition and non-attrition groups. In turn, a relevant auxiliary variable was included in the analysis to help reduce bias associated with this systematic pattern between participants who did and did not drop out of the study.

To investigate the concurrent and predictive relationships among MD stream functioning, exogenous VA and reading achievement, I conducted a 5-wave Cross Lagged Panel Analysis using Full Information Maximum Likelihood Estimation (FIML). Including cross-lagged paths allows one to test for the presence of causal relationships due to the time lag between measurements (Fowler et al., 2012). All constructs were specified as latent variables. In structural equation modelling (SEM), two indicators per latent variable are often sufficient, and tend to produce more theoretically sophisticated models (Hayduk & Littvay, 2012). For the reading decoding latent variable, the two decoding measures within each wave of testing were used as indicators. For the MD stream latent variable, two-three estimates of coherent motion detection from the RDK task within each wave of testing were used as indicators. For the exogenous VA latent variable, the two attention index scores from the LMI task within each wave of testing were used as indicators. Further details regarding how the latent factors were created is provided in the methods section above.

The first model that was tested included all autoregressive paths to explore the presence of stability in MD stream functioning, exogenous VA, and reading ability over time, with larger coefficients meaning more stability in individual differences (Kearney, 2017; van den Boer & de Jong, 2018). MD stream, exogenous VA and reading measures were allowed to correlate at the same points of measurement. These synchronous correlations were used to examine the concurrent relationships between MD stream functioning and exogenous VA, exogenous VA and reading, and MD stream functioning and reading (Kearney, 2017). Cross-lagged paths were included to examine the presence of predictive relationships between the MD stream and reading, and exogenous VA and reading in sequential waves (Fowler et al., 2012; Kearney, 2017). An auxiliary variable, identified during the missing data analysis, was also included.

The Comparative Fit Index (CFI), Root Mean Square Error of Approximation (RMSEA) and Standardized Root Mean Square Residual (SRMR) were reported to examine model fit. Cutoff values indicating a model with very good fit are as follows:  $CFI \geq .95$ ;  $RMSEA \leq .06$ ;

SRMR  $\leq$  .08 (Hu & Bentler 1999 as cited in Zhang et al., 2019). Nonsignificant chi-square values also signal good model fit. However, as the chi-square value depends greatly on sample size and is likely to be significant even in a well-fitting model, use of multiple fit statistics are acceptable alternatives (Fowler et al., 2012; Tanaka, 1987). If this first model fit the data poorly, paths were removed from the model using both statistical and theoretical rationale in order to improve model fit. Differences in fit between models were examined using the chi-square difference ( $\Delta\chi^2$ ) test and the change in the CFI ( $\Delta$ CFI) (Cheung & Rensvold, 2002). A significant difference between model fit was present if the  $p$  value for the  $\Delta\chi^2$  test was  $\leq$  .05 and/or the  $\Delta$ CFI was  $\geq$  .01 (Cheung & Rensvold, 2002).

## Results

### Descriptive Statistics and Missing Data

Participant demographics are reported in Table 1. The sample included a relatively equal representation of subgroups in reading ability, verified by non-significant chi-square test results on the distributions. Descriptive statistics for participant ages are reported in months and were as follows: Wave 1 (M = 81.00, SD = 4.34); Wave 2 (89.24, SD = 4.04); Wave 3 (M = 94.68, SD = 4.04); Wave 4 (M = 102.07, SD = 3.99); Wave 5 (M = 106.61, SD = 3.84). Means and standard deviations for RDK, LMI and reading decoding performance at each time point are reported in Table 2. For the most part, average RDK, LMI and reading decoding performance improved across time.

Sample-based Cronbach's alpha reliabilities for raw LMI scores ranged from 0.72 - 0.82 across waves. Reliability statistics for the RDK and the two reading decoding tasks are detailed in the method section above. IQ measured at Wave 1 had a mean of 96.71 and a standard deviation of 12.52, and all participants met the predetermined criteria for IQ cutoff. Data were examined for violations of statistical assumptions and outliers. Cutoffs for skew and kurtosis were 3 and 10, respectively, as suggested by Kline (2016). All data fell within the cutoffs.

Differences between participant groups with ( $n = 63$ ) and without ( $n = 108$ ) missing data were examined using t-tests, which revealed that no systematic differences were present on variables of interest at baseline between those with and without missing data. However, t-tests revealed that the attrition group (those not present for at least the full five waves) performed more poorly on reading tests at Wave 1 in comparison to the non-attrition group,  $t(169) = 3.925$ ,  $p < .001$ . Hence, elision performance was included as an auxiliary variable at the first timepoint

in the longitudinal analysis. Elision is used to measure phonological awareness ability and is highly correlated with reading ability (Bosse et al., 2007), and was therefore considered to be the most appropriate covariate for accounting for systematic differences among attrition and non-attrition groups in initial reading ability. Differences between attrition groups on the initial indicator variables were eliminated (statistically) by covarying elision (as the auxiliary variable). This eradicated the reading-ability differences between attrition and non-attrition groups, and in turn any systematic bias associated with it.

### **Cross-Lagged Panel Models**

All indicator factors were significant for each latent factor ( $p < .001$ ). Parameters among all models attempted were free to vary. The hypothesized model (Model 1) included 12 autoregressive paths and eight cross-lagged paths (see Figure 1). Model 1 yielded a suboptimal data fit (see Table 3). To try to improve model fit, although all were significant, autoregressive paths for RDK and LMI were removed. The rationale for this was that stability of RDK and LMI performance over time was of less conceptual interest than stability of reading decoding performance over time. Removing these autoregressive paths yielded a model that successfully converged, and although the chi-square fit statistic was poor, the other fit indices were excellent,  $\chi^2(452) = 660.428, p < .001, RMSEA = .052, CFI = .953, SRMR = .049$ ; however, the model had more free parameters than observations. If the number of parameters to be estimated, or the number of free parameters, is less than or equal to number of observations, the model is regarded as overidentified or just identified. If the number of free parameters exceeds the number of observations, then the model cannot be identified (Kaplan, 2009). Thus, in an effort to reduce the number of parameters, all statistically insignificant predictive links between measures of VA and reading were removed from the model (Model 2). This substantially improved the fit of the data compared to Model 1, as indicated by a statistically significant  $\Delta\chi^2$  test and a  $\Delta CFI$  of 0.019 (see Table 3). Finally, Model 2 was compared to a model containing solely reading autoregressive paths while allowing the other latent factors to covary freely (Model 3). This was done to ensure that including predictive pathways from VA to reading decoding fit the data better than not including these pathways. Fit for the model with the predictive pathway between LMI and reading decoding was indeed a better fit than the model with just reading autoregressive paths, as indicated by a statistically significant  $\Delta\chi^2$  test (see Table 3). In turn, Model 2, which contained excellent fit statistics, was retained as the best fitting model (see Figure 2).

As seen in Figure 2, all autoregressive paths for reading decoding were statistically significant, indicating stability in individual reading decoding abilities over the course of the study period. One cross-lagged path, LMI performance in Wave 1 with reading decoding in Wave 2, was significant. This pattern of a cross-lagged effect suggests that earlier exogenous VA predicts subsequent reading ability at that point in reading acquisition, but that the effect does not repeat in subsequent time points. It is important to note that this relationship was found above and beyond the variability and growth in reading accounted for by the reading decoding autoregressive paths. No other cross-lagged paths were significant, showing no other unidirectional associations between the two measures of VA and reading decoding.

Bidirectional correlations are not pictured in Figure 2 for clarity but are included in the model and are detailed in Table 4. Significant correlations were found among RDK and LMI within waves, and among RDK, LMI and reading decoding across waves. Reading decoding in Wave 1 was significantly correlated with RDK performance in Waves 2, 3 and 4, and with LMI performance in Waves 2, 4 and 5. These patterns suggest that at the earliest timepoint, reading ability accounts for significant variance in future VA abilities at most time points, with subsequent measures of reading ability not accounting for any additional significant variance in VA abilities. This also implies that relations between earlier reading ability and later VA ability remain even as children improve in reading. In terms of concurrent relationships, RDK in Wave 1 was significantly correlated with reading decoding in Wave 1, whereas LMI in Wave 3 was significantly correlated with reading decoding in Wave 3. This shows that the roles of different types of VA in contributing to development of reading decoding can change during different points in development. Finally, significant correlations were found between Wave 1 LMI and RDK in Wave 4, Wave 2 LMI and RDK in Wave 3, and Wave 3 LMI and RDK in Waves 4 and 5, suggesting that earlier LMI performance is related to later RDK performance during the first three time points.

### **Discussion**

In order to better understand reading acquisition and difficulty, it is important to study the processes involved in learning how to read. MD stream and exogenous VA processes both play key roles in reading acquisition, performance and impairment (Stein, 2018; Vidyasagar & Pammer, 2009). According to Castles and Coltheart (2004), longitudinal studies are needed to pinpoint early deficits that predict reading ability. Namely, understanding not only the general

nature of reading difficulty but also when VA anomalies might cause struggles in reading as children develop reading skills, can enable us to develop effective interventions targeting the specific anomaly or anomalies (Tulloch & Pammer, 2018). Applying this to the present study, examining not only if but also when MD stream functioning and/or exogenous VA influence reading ability can help to better understand reading acquisition and ultimately to guide effective targeted intervention efforts. Thus, the present thesis represents a substantial advance on cross-sectional studies and addresses existing gaps in the literature by using a multiple-wave, longitudinal study design to examine the relationships among MD stream functions, exogenous VA, and reading ability, as well as the developmental trajectory of these relationships in children across grades 1-3, the period of initial reading acquisition for most children.

A model including autoregressive, concurrent and predictive pathways among and between VA processes and reading decoding was first examined. It was hypothesized that concurrent and predictive relationships among MD stream functioning, exogenous VA and reading decoding, respectively, would be significant throughout all waves of testing. Based on both conceptual and statistical rationale detailed above, a model including only some of the expected pathways was ultimately chosen as the best fitting model. Overall, the analyses showed that the role of visual processing measures are largely constrained to reading abilities at the earliest time points, in terms of both predictive and concurrent links between VA abilities and reading decoding. This reflects the important role of early VA abilities to early reading acquisition.

Average reading decoding performance improved in children over time, indicating expected growth in reading decoding skills across grades 1-3. Average RDK performance also improved over time, except for RDK performance from Waves 2 to 3, which showed a very slight decline. This general pattern of improvement provides evidence for development of the MD stream throughout early childhood, similar to what previous research has found (Armstrong, et al., 2009; Boets et al., 2011; Braddick et al., 2003; Elleberg et al., 2003; Englund & Palomeres, 2012; Kassaliete et al., 2015). Further, average LMI performance improved over time as well, with the exception of from Waves 4 to 5, which showed a large decline. Calculations were reviewed, and the reason for this sudden, unexpected decline is in turn unknown. However, for the most part, these findings align with literature supporting improvement of exogenous VA



and PPC processes over early childhood (Lellis et al., 2013; McDermott et al., 2007; Vidyasagar & Pammer, 1999; Wolf & Pfeiffer, 2014).

The final model showed that individual reading decoding abilities were highly stable over time, similar to what other research has found (van den Boer & de Jong, 2018; van Viersen et al., 2018). This means that future reading decoding performance is dependent on, or predicted by, past reading decoding performance (Kearney, 2017). Recognizing that reading ability improves over time, stability indicates that relative standing in reading skill compared to peers does not change. Namely, although general reading performance improves over time, the pattern of rank order generally does not change, likely unless intensive reading intervention is provided (Denton et al., 2006). This in turn makes it all the more important to remediate early reading difficulties and identify factors that are predictive of said difficulties, such as anomalous VA processes.

Of primary interest, hypotheses regarding predictive relationships between VA factors and reading decoding were partially supported. Predictive relationships between RDK and LMI and subsequent reading decoding, respectively, were hypothesized to be present throughout each wave, with stronger predictive relationships occurring earlier in development. This model showed support for a significant unidirectional relationship from LMI to reading decoding, where LMI at the first time point predicted reading decoding at the second time point. A model including this link fit the data significantly better than an identical model not including this link, showing that exogenous VA has an important role to play in accounting for growth in reading from the end of grade 1 to the first term of grade 2, even after controlling for stability in reading decoding between Waves 1 and 2. However, this predictive relationship was not observed to persist over time, as indicated by insignificant predictive relationships in the first two models attempted, as detailed above. This shows that perhaps rather than predictive relationships between exogenous VA and reading being stronger earlier in development as hypothesized, these relationships are only *present* earlier in development. This aligns with the findings of Franceschini et al. (2012), who concluded that parietal-VA abilities predict reading performance in the very early years of reading acquisition (grades 1 and 2), and in turn that the predictive role this visual factor plays is constrained to emerging reading abilities and earliest development in reading decoding. This shows that exogenous VA may be particularly important for reading decoding abilities occurring very early on in reading development, such as developing initial representations of letters and words.

Despite evidence that earlier MD stream anomalies affect later reading ability (Boets et al., 2011; Gori et al., 2016), no significant predictive relationships were present in the first two models attempted in the current study. This suggests that growth in reading decoding is independent of VA abilities related to MD stream activity (Kruk & Luther Reuban, 2018). This falls in accordance with findings by Kruk and Luther Reuban (2018), who found that rapid automatized naming (RAN), a skill essential for reading decoding, was not predicted by the RDK task, and in turn asserted that RAN development was independent from MD stream activity. This may suggest that MD stream functioning, at least as indexed by the current RDK task, has minimal predictive influence on the development of reading decoding among children in grades 1-3. Alternatively, this finding may mean that MD stream functioning has minimal influence on certain *types* of reading decoding. Kinsey et al. (2004) found a predictive influence of MD stream functioning as indexed by a RDK task on reading decoding of non-word reading, but not irregular word reading. According to the dual route model of reading (Coltheart et al., 2001), novel non-words are read serially (letter by letter), which necessitates fast and accurate VA shifting from one serial position to another. On the other hand, irregular or high frequency words are read using a parallel process, where demands on VA are much less than in non-word reading. In turn, the MD stream may have a larger influence on the processing needed for non-word (letter-by-letter) decoding than irregular word decoding (Kinsey et al., 2004). As the present study used only measures of regular and irregular word decoding, it is possible that this explains why no predictive effects between RDK and reading decoding were found. This shows the importance of examining the influence of MD stream functioning on a wide range of reading decoding types, such as non-word, regular, and irregular word decoding, which would help to obtain a clearer picture of the predictive influence of VA in reading decoding over time.

Similar to hypotheses regarding predictive relationships between VA processes and reading decoding, hypotheses regarding concurrent relationships between VA and reading decoding across time points were also only partially supported. This model provided evidence for a significant, concurrent relationship between VA and reading at only certain time points, showing that MD stream functioning and exogenous VA are significantly related to reading decoding during different periods in development. This model yielded a significant relationship between RDK and reading decoding at Wave 1. This shows evidence for general involvement of MD stream functioning in reading decoding, and of reading decoding in MD stream functioning,

at only this earliest time point. A reason for this finding may echo the potential reason for why predictive relationships were found between LMI performance and reading decoding only at the earliest time point. Namely, that the MD stream's influence on reading decoding performance (and vice versa) is limited to emerging reading abilities. Further, this finding may indicate that MD stream functioning is consistently, concurrently related to *other* processes necessary for reading development. This aligns with the findings of researchers who have found consistent concurrent relationships between coherent motion detection performance and reading fluency in school age children (Englund & Palomares, 2012; Kassaliete et al., 2015; Strait & Palomares, 2012). Although there exists evidence for the MD stream playing a key role in processes necessary for decoding of letters and words (Pammer et al., 2006; Vidyasagar & Pammer, 2009), it is possible that this influence of the MD stream in reading decoding is more clearly reflected through other, higher-level reading processes during the presently measured developmental period, such as reading fluency. More practically speaking, efficient VA may have a role in establishing accurate representations of correct letter orders in words, which could influence basic decoding abilities (involving the efficiency of engaging in letter-by-letter decoding) all the way through to efficient word-level fluency (Vidyasagar & Pammer, 2009). This shows the importance of examining the influence of MD stream functioning on other reading-related processes involved in reading acquisition and development, across a wider span of development.

It is important to note that a significant concurrent relationship was also found between LMI performance and reading decoding at Wave 3. However, the negative coefficient (-0.313) indicated an inverse relationship, that is, higher LMI task performance was associated with lower reading decoding ability, and vice versa. This may have occurred as a product of rapid improvement in LMI performance from the previous wave, associated with a relatively small improvement in reading decoding performance from the previous wave. Furthermore, a potential reason why significant, positive concurrent relationships were not found between LMI and reading decoding at any time point may have been because of the nature of the model. Namely, the role of visual processing measures were constrained to earliest reading decoding abilities. The variability in reading growth that could have been identified in the bulk of subsequent concurrent links was likely accounted for by the significant concurrent relationship between RDK and reading decoding in Wave 1, and the significant predictive relationship between LMI

Wave 1 and reading decoding Wave 2. This may explain the lack of significant, positive concurrent relationships found between LMI and reading decoding in the current study.

In addition to the concurrent bidirectional relationships between VA processes and reading decoding found within waves, additional bidirectional relationships between VA processes and reading decoding were found across waves; revealed by allowing parameters in the final model to be free to vary. Wave 1 reading decoding was significantly correlated with RDK performance in Waves 2, 3 and 4, and with LMI performance in Waves 2, 4 and 5. Despite being correlational, the temporal nature of these relationships is consistent with the suggestion that the variance that initial reading decoding accounts for in subsequent VA was already present at the first wave of testing. Stated another way, reading decoding at Wave 1 differentiates good from poor readers in their VA abilities later on in development, in that reading decoding at later time points does not account for additional significant variance in subsequent VA abilities. Further, as the covarying relationships occur between the earliest-measured reading and later VA processes, we can conclude that subsequent reading ability improvements do not necessarily mean that there is a role of reading growth in subsequently improved VA. All in all, these findings indicate that what happens in reading decoding achievement at the very early periods has longer term influences on later visual processes, emphasizing the importance of reading in the beginning stages on initial and later visual processes.

Finally, several significant correlations were found between earlier LMI performance in Waves 1-3 and subsequent RDK performance. This suggests that exogenous VA ability is related to later MD stream ability and provides evidence for the general interrelationships between the two factors over time. This suggestion would be supported by further research looking at the influence of both of these VA factors on reading longitudinally.

### **Limitations and Future Directions**

One primary limitation of this study is that although CLPM can reveal information regarding temporal relationships, it cannot give information regarding causality (Kearney, 2017). This is especially so in the case of a study that takes place across a fairly short period of time in reading acquisition, such as this one. In turn, although the predictive link found in this study between exogenous VA and reading decoding is necessary for making causal conclusions, it is not sufficient to assert that exogenous VA has a *causal* role in reading decoding performance. Without data on pre-readers, it is difficult to assert any causal relationships on whether pre-existing visual anomalies are associated with early reading

difficulties, or whether visual anomalies are the product of limited exposure to reading often experienced by poor readers. In the sample in the current study, children may already have had early reading experience before the first measurement time point. In order to explore possible causality, future studies should examine the relationships between MD stream functioning, exogenous VA and reading decoding over a longer period of time, especially prior to the start of reading instruction, as well as in connection with visually based interventions for visual processes associated with reading abilities. This would allow for the type of evidence needed to deduce causal relationships, would provide greater insight into the development of reading difficulty, and would specify how and when reading acquisition is associated with VA processes. Further, this proposed extended research would give new information on whether MD stream functioning and exogenous VA influence reading decoding ability as children begin to acquire the fundamentals of decoding prior to grade 1, and then later in reading development, beyond grade 3 as fluent decoding emerges; these research initiatives may give light to additional concurrent and predictive relationships that were not found in the present study.

A second limitation of this study is that the best fitting model did not include all potential predictive links between RDK and reading decoding, and LMI and reading decoding. This makes the conclusion that the only significant predictive relationship that exists is between LMI at Wave 1 and reading decoding at Wave 2 a preliminary one. However, other attempted models, despite their imperfections, showed that the predictive relationship between LMI at Wave 1 and reading decoding at Wave 2 was in fact the only significant one. Nonetheless, future research should further explore the presence of these relationships (for example, using larger sample sizes) to make more definitive conclusions regarding the predictive relations between MD stream functioning and reading decoding, and exogenous VA and reading decoding over time.

A third limitation of this study is that it only examined certain VA and reading processes. The decision to examine the chosen variables was made based on the strong anatomical link between the MD stream and the PPC (Laycock et al., 2006; Facoetti et al., 2000), as well as the influence of both MD stream functioning and exogenous VA on processes involved in reading decoding (Cornelissen et al., 1998; Cornelissen & Hansen, 1998; Husain, 1991; Laycock et al., 2006; Levy et al., 2010; Vidyasagar & Pammer, 2009). However, a combination of other VA and reading processes should be examined using a similar longitudinal study design, which would shed further light on the relationships between VA and reading. For example, various other VA processes such as the VA span (Bosse et al., 2007), visual search ability (Skottun, & Skoyles,

2007), symmetry of VA distribution (Facoetti & Turatto, 2000) and selective VA (Lancaster et al., 2021), just to name a few, have all been found to influence reading decoding. Additionally, MD stream functioning and exogenous VA have been found to be related to other types of reading decoding such as non-word decoding (Kinsey et al., 2004), as well as other reading processes necessary for proper reading development, such as reading fluency (Englund & Palomares, 2012, Kassaliete et al., 2015) and comprehension (Solan et al., 2007). The above relationships are especially important to explore, as VA anomalies often cooccur (Tafti et al., 2014) and reading decoding difficulties are typically associated with other types of reading difficulties (Gillon, 2017).

A fourth limitation of this study is that it examined the relationships between VA and reading decoding in good and poor readers combined. This decision was made as plenty of research has found the relationships between MD stream functioning, exogenous VA and reading decoding to hold irrespective of reading ability (Cornelissen et al., 1998; Cornelissen & Hansen, 1998; Husain, 1991; Laycock et al., 2006; Levy et al., 2010; Vidyasagar & Pammer, 2009). Research has also found the development of MD stream functioning, exogenous VA and reading decoding to follow similar patterns among both good and poor readers, in that all three abilities generally improve with age (Kassaliete et al., 2015). Further, it was expected that the sample size would be insufficient for testing all desired pathways among separated good and poor reader groups as it would have likely led to more parameters than observations (Kaplan, 2009). However, as emerging research *has* found differences in the development of MD stream functioning among good and poor readers (Younger et al., 2017), it is important for future studies to examine the relationships between MD stream functioning, exogenous VA and reading decoding in children with differing reading abilities, to see how these relationships manifest over time.

Finally, although past research has not found evidence for reciprocal relationships between MD stream functioning and reading skills (Boets et al., 2011; Gori et al., 2016; Joo et al., 2017; Laycock et al., 2006), presumably meaning that reciprocal relationships would not be found for exogenous VA either due to the strong anatomical connection between the MD stream and the PPC (Laycock et al., 2006), future research should nonetheless examine the reciprocal links between VA and reading decoding. Namely, it is possible that anomalous MD stream functioning and exogenous VA may not cause poor reading and may instead be a *result* of reading difficulty due to poor or insufficient reading

experience and in turn less practice with MD stream and exogenous VA skills (Ramus, 2003; Talcott & Witton, 2002). In turn, it would be important to examine this potential relationship over time to give better insight into the directionality of the relationships between VA and reading. Testing these reciprocal relationships would also necessitate the need for including MD stream and exogenous VA auto regressive links in the model, which would provide useful information regarding the stability in MD stream and exogenous VA over time.

### **Conclusion**

Overall, this study provided evidence for VA deficits often seen in reading difficulty extending to higher-level visual functions in the PPC, specifically exogenous PPC functions receiving their input from the MD stream, rather than being specific to solely lower-level MD stream deficits (Iles et al., 2000). This can be seen by the significant unidirectional and bidirectional relationships between LMI and reading decoding across development, as well as the significant correlations between earlier LMI and later RDK. This shows the importance of examining the influence of both higher and lower-level VA processes in reading ability.

Importantly, the significant relationships between VA and reading tended to occur at the very earliest stage of reading measured in the present study. These results have important clinical implications in that they show that VA has important concurrent and predictive relationships with very early reading ability and potentially pre-reading skills involved in letter and letter-cluster learning. Given these relationships, it could be particularly important to implement interventions to remediate MD stream functioning and exogenous VA before grade 1, in order to allow for potential improved reading acquisition to emerge without possible visual anomalies impairing reading development. The results of this study are consistent with feasibility or potential of such interventions being effective for aspects of reading difficulty that are associated with visual attention anomalies. As reading is an essential part of children's education, it is important to identify the early anomalies associated with reading difficulty and to demonstrate how they influence reading ability over the early years of reading acquisition. This can allow for earlier and more effective prevention, screening, and intervention measures.

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Table 1

*Participant Demographics at Wave 1*

Demographics		Frequency (Percent)
N		171 (100)
Sex	Male	94 (54.7)
	Female	77 (44.8)
Reader Group <sup>a</sup>	Good	69 (40.35)
	In-Between	50 (29.24)
	Poor	52 (30.41)
SES	High	59 (34.3)
	Middle	82 (47.7)
	Low-Middle	13 (7.6)
	Low	17 (9.9)
School Division	1	49 (28.5)
	2	68 (39.5)
	3	54 (31.4)
School	1	20 (11.6)
	2	10 (5.8)
	3	12 (7.0)
	4	7 (4.1)
	5	19 (11)
	6	33 (19.2)
	7	16 (9.3)
	8	13 (7.6)
	9	5 (2.9)
	10	13 (7.6)
	11	12 (7)
	12	11 (6.4)
Primary Language	English	154 (89.5)
	Other	17 (10.5)

*Note.* Division and School names are not listed to protect confidentiality. SES = Socio-Economic Status. <sup>a</sup>Coded according to performance on diagnostic reading measures.

Table 2

*Means and, Standard Deviations for Age, Visual Attention and Reading Decoding Tasks Across Waves*

Wave	Variable	N	M	SD	Minimum Statistic	Maximum Statistic
1	RDK	170	52.68	23.89	11.04	100
	LMI	170	0.28	0.26	-.24	.85
	WCWI	171	25.01	15.6	10	69
	WRATRE	161	20.43	3.913	18	33
2	RDK	156	44.47	23.91	11.74	100
	LMI	156	0.30	0.32	-.82	.90
	WCWI	149	40.17	16.02	28	82
	WRATRE	148	25.05	5.397	20	46
3	RDK	155	45.06	24.12	11.80	100
	LMI	155	0.41	0.28	-.17	.90
	WCWI	153	48.02	14.98	34	81
	WRATRE	153	27.1	5.008	24	42
4	RDK	141	41.13	22.49	14.17	100
	LMI	137	0.42	0.29	-.30	.90
	WCWI	141	55.54	14.31	41	90
	WRATRE	139	29.84	0.432	25	44
5	RDK	137	38.24	1.84	12.52	100
	LMI	137	0.27	0.31	0.51	.85
	WCWI	134	61.12	13.52	43	90
	WRATRE	133	31.58	0.493	25	44

*Note.* LMI = line motion illusion; RDK = random dot kinematogram; WCWI = Woodcock Reading Mastery Test-Revised Word Identification subtest; WRATRE = Wide Range Achievement Test, 3<sup>rd</sup> Edition Reading subtest. Units of measurement included: attention index units for LMI; percent dot coherence threshold for RDK; total correct for each of WCWI and WRATRE.

MAGNOCELLULAR-DORSAL STREAM AND EXOGENOUS VISUAL ATTENTION

Table 3

*Model Fit Information*

Model Name	$\chi^2$	<i>df</i>	<i>p</i> value	CFI	RMSEA	SRMR	$\Delta\chi^2$	<i>df</i>	<i>p</i> value	$\Delta$ CFI
Model 1	780.163	492	<.001	0.936	0.059	0.114				
Model 2	668.797	466	<.001	0.955	0.05	0.052				
Model 3	674.242	467	<.001	0.954	0.051	0.056				
Difference between Model 1 and Model 2							111.366	26	<.001	0.019
Difference between Model 2 and Model 3							5.442	1	0.02	0.001

*Note.* Model cut-offs are as follows: Chi-square ( $p > .05$ ), CFI  $\geq .95$ , RMSEA  $\leq .06$ , SRMR  $\leq 0.08$ , chi-squared change ( $p \leq .05$ ) and CFI difference  $\geq .01$ .



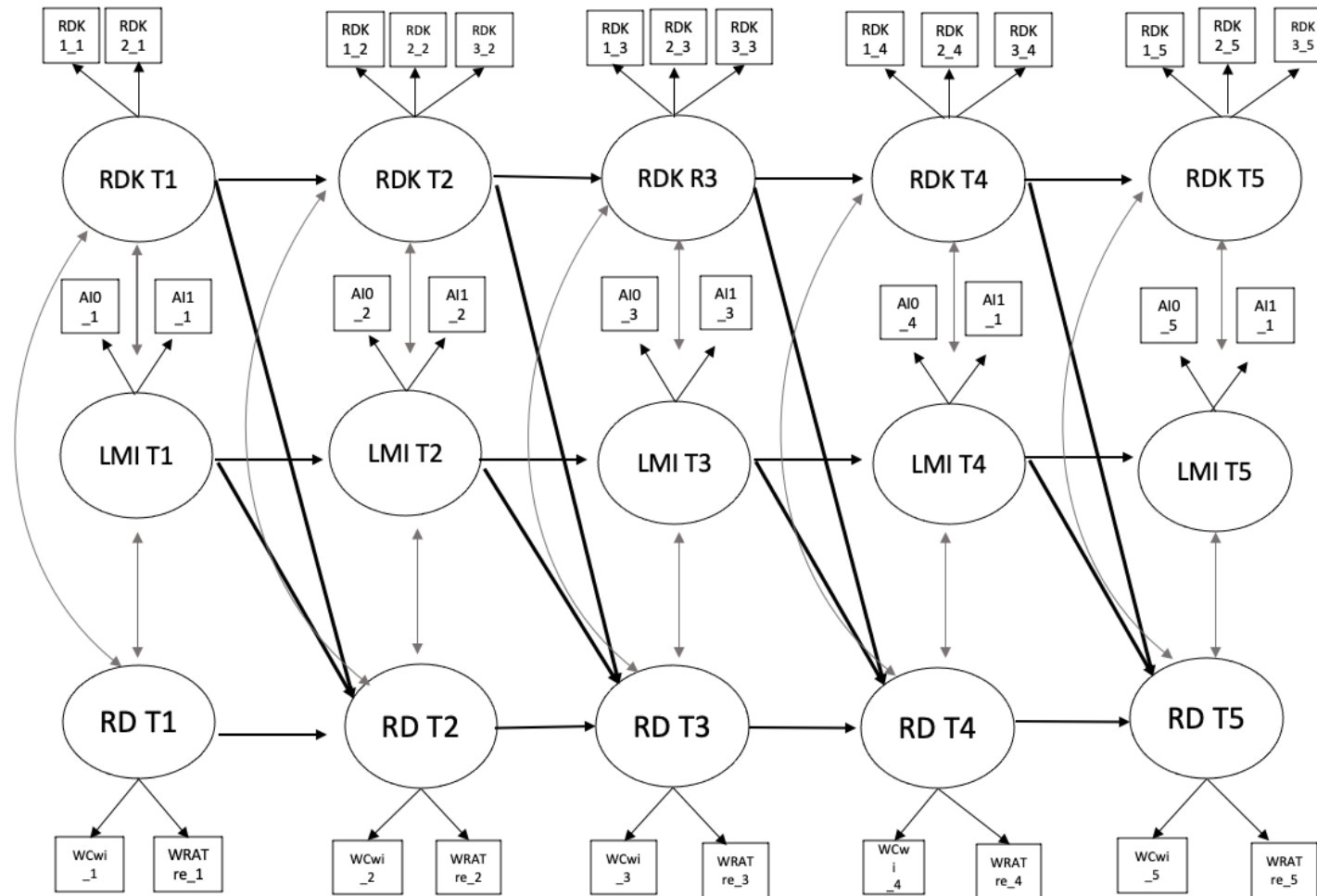
Table 4

*Standardized Coefficients among Bidirectional Links included in Model 3*

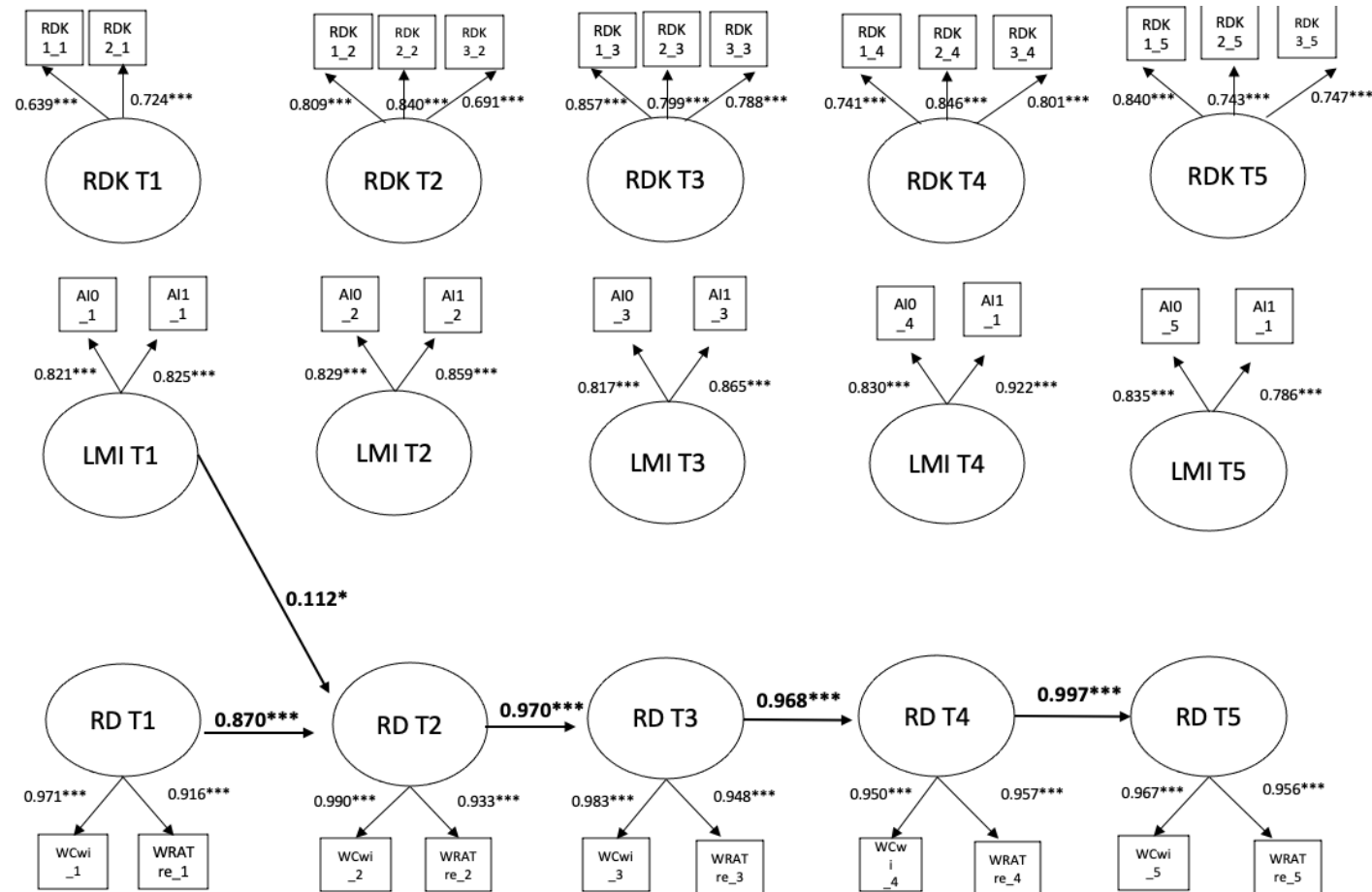
Measure	RDK T1	RDK T2	RDK T3	RDK T4	RDK T5	LMI T1	LMI T2	LMI T3	LMI T4	LMI T5	RD T1	RD T3
RDK T1												
RDK T2	0.578***	---										
RDK T3	0.656***	0.627***	---									
RDK T4	0.759***	0.590***	0.859***	---								
RDK T5	0.659***	0.735***	0.870***	0.931***	---							
LMI T1	-0.022	-0.069	-0.037	-0.218*	-0.176	---						
LMI T2	-0.069	0.019	-0.208*	-0.11	-0.163	0.229*	---					
LMI T3	0.014	-0.099	-0.106	-0.216*	-0.219*	0.453***	0.498***	---				
LMI T4	0.027	-0.121	-0.061	-0.109	-0.148	0.555***	0.439***	0.634***	---			
LMI T5	-0.087	0.025	-0.060	-0.057	-0.036	0.293**	0.451***	0.503***	0.581***	---		
RD T1	-0.370***	-0.270***	-0.166*	0.340***	-0.311	0.072	0.287***	0.166	0.242**	0.377***	---	
RD T3								-0.313***				---

All other correlations are not significant. T = time, RDK = random dot kinematogram, LMI = line motion illusion, RD = reading decoding. RD T2, RD T4 and RD T5 are not included in this table as the correlations between these and other factors were not included in the model. Correlations between RD T3 and other factors besides LMI T3 are left blank in this table as they were not included in the model.

\* $p \leq .05$ . \*\* $p \leq .01$ . \*\*\* $p \leq 0.001$ .

**Figure 1***Visual Attention and Reading Hypothesized Cross-Lagged Model*

*Note.* T = time, RDK = random dot kinematogram, LMI = line motion illusion, RD = reading decoding

**Figure 2***Visual Attention and Reading Final Cross-Lagged Model*

*Note.* T = time, RDK = random dot Kinematogram, LMI = line motion illusion, RD = reading decoding. Values represent standardized coefficients. The coefficients for the bidirectional links included in the model among the latent variables are given in Table 4.  
 \* $p \leq .05$ . \*\* $p \leq .01$ . \*\*\* $p \leq .001$ .