Attention Resolution Efficiency in Children Varying in Reading Ability and Age: Can Better Readers who are Older "Find Waldo" the Fastest?

by

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Abstract

Attention Resolution (AR) modulation is a visual-spatial process used to isolate, in attention, a specified item in a cluttered visual display, such as the face of "Waldo" pictured in a crowd of faces or a specified letter in a written word; the speed with which AR adjustments take place is proposed to reflect AR efficiency. Children develop more precise AR with age (Wolf & Pfeiffer, 2014) enabling isolation of more-closely spaced items over time. The print size needed for optimal reading speed also decreases with age, perhaps suggesting more efficient AR modulation with practice in isolating letters during reading. Struggling readers accumulate progressively less reading exposure over time than do typical readers, and also require wider letter spacing to reach optimal reading speed, potentially indicating an efficiency-based AR deficit linked to limited reading exposure in struggling readers. AR precision and efficiency were studied in 201 children varying in reading ability in Grades 2 and 6 using a dot-tracking task. Children were asked to track and subsequently identify a target dot after it moved among visually identical distractor dots, passing the distractors at different distances (precision) and speeds (efficiency). Across grade and reader groups, relative dot-tracking accuracies across distance and speed conditions indicated additive effects of precision and efficiency manipulations on tracking performance. Reader group analyses pointed toward a general developmental delay of AR modulation in struggling readers, who performed consistently more poorly than better-able readers in their own age group regardless of distance or speed condition. Grade 6 struggling readers outperformed reading-age-matched participants in Grade 2, suggesting that chronological age was a stronger predictor of AR modulation than was reading exposure. Reader group differences are discussed in light of exploratory analyses on reading-related factors found to predict AR task performance.

Key words: development, reading disability, visual attention, spatial resolution, efficiency

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Dedication

This thesis is dedicated to the children, families, and schools
that participated in this study, as well as to any student who is
fighting an invisible battle, such as a reading disability,
while pursuing their education.

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Attention Resolution Efficiency in Children Varying in Reading Ability and Age: Can Better Readers who are Older “Find Waldo” the Fastest?

The indispensible roles of reading and writing become evident early in life. Children are introduced to alphanumeric systems in Kindergarten and are expected to switch from “learning to read” to “reading to learn” by the fourth grade. Unfortunately, a sizeable portion of children struggle to learn to read. Reading disability (RD) is characterized by difficulties in accurately and fluently recognizing and spelling words, despite having at least average intelligence (IQ) and adequate educational opportunities. Difficulties should also not be better accounted for by socioeconomic status or sensory impairment. Approximately 18% of children read at a below-average level significant enough to impair expected academic progress (OECD, 2014).

Consensus on all causal facets of RD is far from being reached (e.g., Bosse, Tainturier, & Valdois, 2007); however, a core deficit in phonological processing that impairs learning of letter-sound connections is widely accepted (Vellutino, Fletcher, Snowling, & Scanlon, 2004). Yet some individuals with RD perform well on phonological tasks (Valdois et al., 2003) and reading fluency deficits often remain after successful phonological interventions (Wolf, Rourke, Lovett, Cirino, & Morris, 2002). Phonological explanations, although scientifically validated, are not sufficient to account for all aspects of reading difficulty, and in particular aspects related to reading speed.

Visuo-attentional processes may play an additional causal role in RD, at least for some members of this highly diverse population (Gori & Facoetti, 2015). Indeed, various types of attentional deficits have been observed in individuals with RD. For example, processes involving the magnocelluar-dorsal stream of visual processing are impaired in a substantial number of RD cases, such as poor sensitivity to high temporal and low spatial frequencies (Stein, 2001).

Deficits are also observed in the attentional orienting neural system subserved by the dorsal stream; children with RD do not benefit from attentional orienting cues in the same way as typical readers, and show “sluggish” attentional shifting patterns (Ruffino, Gori, Boccardi, Molteni, & Facoetti, 2014). A causal role of these deficits was implicated in a three-year longitudinal study that measured attention orienting deficits prior to reading instruction, finding that these deficits predicted reading acquisition through Grade 2 (Franceschini, Gori, Ruffino, Pedrolli, & Facoetti, 2012). In another line of research, Bosse et al. (2007) showed that a significant proportion of children with RD demonstrate a visual attention span (VAS) deficit (defined as the number of letters that can be processed in parallel) but not a phonological deficit. Following up on these findings using functional magnetic resonance imaging, Peyrin et al. (2012) compared two cases with RD who experienced a double dissociation in their phonological and VAS skills. The authors found a distinct pattern of brain activation and reading errors associated with each deficit. The phonological deficit was associated with decreased inferior frontal gyrus activity compared to the control group during an auditory rhyming task while the VAS deficit was not. On the other hand, the VAS deficit was associated with decreased parietal lobe activation compared to the control group during a visual categorization task while the phonological deficit was not. In regard to reading errors, the VAS deficit was uniquely associated with poor irregular word reading skills based on grapheme parsing errors whereas the phonological deficit was uniquely associated with poor pseudo-word spelling skills.

The culmination of findings in these diverse fields of research makes it clear that anomalous visual-attentional processes are present in RD, and may in fact be key and unique components of the disability. Further research exploring different facets of attentional anomalies will help elucidate a wider breadth of difficulties faced by these children while learning to read. One such area that has yet to be investigated in this population is attention resolution.

Attention Resolution

Attention resolution (AR) refers to the precision with which visual areas can be selectively isolated and localized within conscious, attentive perception. Proficiency with selecting precise visuo-spatial coordinates serves important functions during visual analysis. First, the selected area defines the space over which visual features are integrated and scrutinized, as is necessary to do when identifying an object or analysing the characteristics of a texture. More importantly, neighbouring areas are excluded from integration in order to separate the selected area or item from its surroundings, a process that Intriligator and Cavanagh (2001) refer to as *individuation*. Individuation permits an item to be “tagged” so it can be localized and tracked through visual space without being confused with neighbouring items.

The optimal level of visual-spatial precision needed for goal completion varies according to task demands. For example, catching a football requires only coarse selection given the size of the ball and the ease with which it can be distinguished from the surrounding sky. Other goals such as ‘finding Waldo’ require a more precise resolution because fine-grained details must be isolated from within a busy visual scene. Even for these more demanding tasks involving smaller visual areas, however, AR modulation is quite routine and automatic for most everyday activities. Areas of interest are simply brought into focal vision where AR can be more precise than is typically needed. Individuals with healthy visual attention are proficient (both efficient and flexible) in adjusting AR to meet task demands (Yeshurun, Montagna, & Carrasco, 2008). That is, they can quickly modulate the grain of resolution to isolate both small and large visual areas, depending on the goal of the observer.

The limits of AR become evident in circumstances where the spatial resolution of visual acuity exceeds that of attentional selection; that is, when the separation between two points is within the limits of visual acuity, even though it is impossible to isolate and localize one of those points relative to the other. The limits of AR as well as the distinction between visual acuity and AR are best demonstrated using tasks completed in peripheral vision where visual acuity is poorer. While fixating on the cross in Figure 1 (Intriligator & Cavanagh, 2001), the presence of multiple homogeneously spaced vertical black lines is clearly apparent; however, attempting to select a particular line using attention alone, say the fourth line from the left, is extremely difficult to do if not impossible.

Figure 1. Demonstration of the difference between resolving items by visual acuity versus attention. While fixating the cross, the presence of multiple vertical lines is clearly apparent in peripheral vision. Nevertheless, it is nearly impossible to select a particular centrally positioned line using attention alone (from Intriligator & Cavanagh, 2001).

This same phenomenon seems to occur in focal vision as well, but it occurs on a much smaller scale. For example, participants in Landolt (1891) were unable to enumerate lines that were spaced apart at 5 minutes of an arc (arcmin), even though the lines remained perceptually distinct and were thus within the limits of visual acuity. Enumeration requires each item to be “tagged” so as to not count the same item twice. Inaccurate counting therefore indicates a failure to individuate. Kowler and Steinman (1977) similarly found foveal counting inaccuracies when lines were spaced between 7 and 14 arcmin apart. As Intriligator and Cavanagh (2001) point out, these results “imply that the finest spacing at which attention operates may be on the order of 5 to 10 arcmin at the fovea–a value substantially coarser than the finest spacing that can be visually resolved at the center of gaze, about 1 arcmin" (p. 176).

Proficiency with AR modulation in both foveal and peripheral vision has intuitive relevance for learning to read. Multiple closely-spaced letters at various eccentricities must be quickly and accurately individuated before those letters (and subsequently words) can be identified. Imprecise area selection could impair letter identification due to erroneous feature integration across multiple letters, or might also result in spatial confusion of letter positions due to poor localization of items relative to others within the selected area. Increased positional uncertainty of letters is indeed reported in dyslexia literature (Collis, Kohnen, & Kinoshita, 2013; Whitney & Cornelissen, 2005). Collis et al. (2013) further noted that transposition errors occurred most frequently for middle letters (e.g., slat read as salt), where AR demands are presumably higher.

Less proficient AR modulation in struggling readers could contribute to these and other reading effects (e.g., fluency deficits) in at least two different ways. One possibility is that the fundamental limit of AR precision may be wider in struggling readers than in typical readers. In this case, struggling readers would require wider spacing between letters before letter individuation could occur at all. Alternately, and as is hypothesized in the current study, struggling readers may be able to reach similar levels of AR precision as typical readers; however, they may be less efficient in modulating AR. In this case, struggling readers would require more time and effort to reach the same levels of precision as typical readers. The speed at which AR can be modulated to the required level of precision is defined here as AR efficiency.

The primary "AR efficiency hypothesis" of the current study – that struggling readers are less efficient in modulating AR – is consistent with the reading fluency deficits that are observed in struggling readers with accurate decoding skills (given that decoding requires letter isolation for identification; Wolf et al., 2002). Moreover, perceptual processing speed is considered to be a key component of RD (Bogon et al., 2014; Lobier, Dubois, & Valdois, 2013; Stenneken et al., 2011) and is thus of particular interest as a potential factor that can differentiate between the AR modulation abilities of typical versus struggling readers. Consistent with this view, O'Brien, Mansfield, and Legge (2005) found that children with RD required larger print sizes (wider letter spacing) than reading-ability-matched controls in order to reach their fastest reading rate. Furthermore, Zorzi et al. (2012) improved both the accuracy and rate of reading for children with RD by widening letter spacing of equivalently difficult passages of text (see also Perea, Panadero, Moret-Tatay, & Gómez, 2012, for similar results). Wider letter spacing likely has such a dramatic impact on reading speed for children with RD by facilitating letter isolation, perhaps by reducing the degree of AR modulation that is required, thus placing less strain on visual-attentional systems that are operating inefficiently.

Crowding

Some of the hypothesized mechanisms by which AR modulation deficits could impair reading, including positional uncertainty and erroneous feature integration, are shared by another reading-limiting construct called crowding (Levi, 2008). Crowding is a well-documented and universally experienced phenomenon wherein an item that is easily resolved when presented in isolation becomes unrecognizable when flanked by other items (see Figure 2). In fact, the uncanny resemblance between the constructs of AR and crowding led He, Cavanagh, and Intriligator (1996) to explicitly link them as causally related, stating that "without distracters, perception of spatial details is limited by conventional visual resolution. However, when several items are presented, perception of the spatial details of a particular item seems to depend on the ability of attentional processes to isolate the item" (p. 336).

Figure 2. Demonstration of the effect of crowding on letter identification. While fixating the central cross, it is possible to resolve the isolated letter 'r' in the left periphery, whereas the flanked 'r' in the right periphery is indecipherable. Notice that both the left and right 'r's are identical in form, size and eccentricity. It is only the presence of flanking letters on the right-hand side that impairs letter identification (from Pelli et al., 2007).

Figure 2 makes apparent the limitation that crowding places on reading. Notice the relative difficulty of identifying the central 'r' of the letter triplet while fixating the central cross as opposed to the smaller cross on the right. In the latter case, the flanked 'r' is more easily identified because it occupies a more central eccentricity. The minimum distance between target and flankers at which flankers no longer impair target identification is called the critical spacing. Importantly, the critical spacing between target and flankers increases with eccentricity, such that the further into the periphery a target appears, the further flankers must be from the target for accurate identification (Bouma, 1970). Given the constant spacing between letters in text (with the exception of spaces between words), the spacing between peripheral letters eventually exceeds the associated critical spacing, rendering letters beyond that eccentricity unidentifiable.

Crowding thus places a fundamental and purely visual limit on the number of letters that can be resolved in a single fixation, also referred to as visual span capacity (Pelli et al., 2007). Identifying fewer letters per fixation has a direct impact on reading speed, as more fixations are required to cover a given amount of text. Legge et al. (2007) found that for each additional letter in visual span capacity, reading speed increased by a dramatic 39%. Abnormally impairing crowding effects due to AR deficits in RD would be particularly detrimental for visual span-related reading outcomes. For instance, typical readers are able to decode most words within a similar time frame within a single fixation. In contrast, children with RD demonstrate length effects, whereby the reading time and the number of saccades per word increases as words become longer (Di Filippo, de Luca, Judica, Spinelli, & Zoccolotti, 2006; Hawelka & Wimmer, 2005). Sufficiently low visual span capacities also provide a parsimonious explanation for reading speed deficits that often persist after phonological interventions (Wolf et al., 2002).

It should be noted that the role of AR in typical crowding effects has been vigorously debated, and that alternative explanations attribute crowding to pre-attentive stages of processing (Levi, 2008). Regardless of whether or not crowding begins pre-attentively, attention appears to have at least a moderating role in the extent of crowding effects, as suggested by the effects of experimental manipulations on the allocation of attentional resources during crowded target processing. For example, crowded items are processed more slowly when attentional resources are distributed with another attentionally demanding task (Dakin, Bex, Cass, & Watt, 2009) Also, Yeshurun and Rashal (2010) demonstrated that pre-cueing a crowded target's upcoming location reduced the critical spacing between target and flankers, presumably because the pre-cue facilitated the allocation of attentional resources to that location (although Scolari, Kohnon, Barton, & Awh, 2007, failed to find a pre-cueing effect). Event-related potential (ERP) studies show more concrete support for an attentional contribution toward crowding effects. Bacigalupo and Luck (2015) found that N2pc, an attention-based ERP component, decreases in amplitude as crowding becomes more severe. N2pc suppression suggests that an attentional mechanism – normally active when isolating a target from flankers – fails when the target is perceived as crowded. Similarly, Chen et al. (2014) found an association between severity of crowding and ERP suppression of the C1 component. C1 is the earliest emerging ERP component, peaking 50

– 70 ms post-stimulus, and is thought to reflect feed-forward processing in visual cortex area V1. Critically, C1 suppression was evident when completing the crowded target identification task (attended condition) but not when stimuli appeared while participants completed another task.

The latter result aligns well with the Hierarchical Sparse Selection (HSS) model of crowding (Chaney, Fischer, & Whitney, 2014). According to the HSS, information encoded in the visual cortex is extracted for conscious (reportable) perception through connections to frontal-parietal attentional regions (a premise consistent with neural processes proposed to differentiate reportable versus non-reportable conscious awareness; Lamme, 2003). However, frontal-parietal neurons are only connected to a subset of neurons in each visual processing area (Kaas & Lyon, 2007). This “sparse selection” of visual neurons limits the amount of information that can be extracted by attention for conscious awareness. When items are too closely spaced, an ambiguous “readout” of those items makes them appear crowded. The fact that Chen et al. (2014) found C1 suppression in the attended condition only corroborates the notion that it is while attempting (with attention) to extract information from the visual cortex that items become “crowded” (their neural activity is suppressed).

Chaney et al. (2014) also speculate that connections between the frontal-parietal and visual cortices proliferate in response to attentional training. Indeed, reliable reductions in critical spacing have been found after sufficient perceptual training in identifying crowded targets (6000 trials in Chung & Truong, 2013). These findings suggest that attentionally-based improvements in crowding occur over extensive periods of training rather than in response to immediate manipulations of attentional allocation (e.g., pre-cues, re-directed attention).

In summary, AR modulation is proposed to underlie individuation of closely spaced items in visual space. Attentional mechanisms operate on a coarser scale than visual acuity, acting beyond mere perception of a gap between items. Further responsibilities of AR include localizing points relative to one another, and in the case of objects, accurately defining spaces for within-object feature integration while inhibiting input from surrounding objects. AR functions are intuitively relevant for reading and learning to read as reading abilities rely heavily on identifying letters situated in densely packed text. It is no surprise, then, that AR has been causally implicated in crowding effects, albeit with some controversy. Recent research seems to increasingly point toward attentional mechanisms in crowding, although the relative roles of attentive versus pre-attentive mechanisms warrants extensive further research. Regardless of whether or not typical crowding is a primarily attention-based mechanism, AR deficits in RD can only exacerbate pre-existing crowding effects. Abnormal visual crowding as a result of less efficient AR modulation is therefore proposed to have a unique negative impact on reading ability, and particularly on reading fluency over and above phonological decoding processes.

Crowding Effects in Reading Disability

Evidence supporting abnormal crowding effects in RD emerged in the 1970s when Bouma and Legein (1977) demonstrated for the first time differences between typical and struggling readers' identification of flanked, but not isolated, letters. Not only that, correlations between crowded-letter-identification and reading ability also emerged. Differences between typical versus struggling readers in crowded letter identification have been replicated (e.g., Callens, Whitney, Tops, & Brysbaert, 2013; Gori & Facoetti, 2015; Martelli, Filippo, Spinelli, & Zoccolotti, 2009) with many researchers observing performance at least one standard deviation below the control group in a significant proportion of children with RD (Bouma & Legein, 1977; Spinelli, De Luca, Judica, & Zoccolotti, 2002). Some studies of children with RD further observed particularly strong crowding effects in parafoveal vision (Bouma & Legein, 1977;

Geiger & Lettvin, 1987; Moll & Jones, 2013) – an area used extensively to guide saccadic eye-movements while reading (Bellocchi, Muneaux, Bastien-Toniazzo, & Ducrot, 2013).

Martelli et al. (2009) examined the rate at which critical spacing increased with eccentricity using a flanked letter paradigm presented at five different eccentricities. The rate at which critical spacing increased with increasing eccentricity was disproportionally fast, and also more variable, in children with RD compared to the control group. In a second experiment looking at reading rate as a function of print size, Martelli et al. showed that the reading rate of both RD and control children increased with print size up until a critical point at which reading rate levelled out (albeit at a slower maximum rate for the RD group). Importantly, the print size at which no further gains in reading rate were achieved (the critical print size) was significantly larger for RDs than controls. Note that print size is a proxy for critical spacing given that the spacing between letters increases with print size, while letter size is itself robust to crowding (Pelli et al., 2007). Interestingly, the rate at which the reading speed of children with RD changed as a function of print size closely mapped onto an estimation of control participants' data when adjusted to two degrees eccentricity. The authors concluded that typical readers' peripheral reading may be prototypical of foveal reading in RD.

Controversy surrounding the interpretation of these findings arises, however, from the predominant use of letters as stimuli. Learned familiarity with letters protects against crowding effects specifically for letter strings (Grainger, Tydgat, & Isselé, 2010). Huckauf and Nazir (2007) posited that this protection most likely emerges due to top-down influence of mental representations for letters and words (consolidated neural networks for rapid processing of letters). The *superiority effect* in crowding attests to the presence of top-down effects: recognition of crowded letters improves as trigrams become more word-like (Bricolo, Salvi, Martelli, Arduino, & Daini, 2015). Mental representations of letters and orthographies are known to be of poorer quality for individuals with RD (Cao, Bitan, Chou, Burman, & Booth, 2006). Some researchers’ failure to replicate crowding differences between typical and struggling readers using non-linguistic stimuli thus places doubt on an underlying attentional mechanism of crowding deficits (Bellocchi & Bastien-Toniazzo, 2007; Shovman & Ahissar, 2006). Nevertheless, methodological choices in these studies limit those conclusions as well. For example, Shovman and Ahissar (2006) measured foveal crowding in adults even though foveal crowding is only supported in children (Levi, 2008; Norgett & Siderov, 2014). Other studies used complex letter-like stimuli (Bellocchi & Bastien-Toniazzo, 2007; Shovman & Ahissar, 2006) which, although free from phonological or linguistic confounds, still engages unrelated visual processes involved in feature analysis and integration, thus failing to isolate the impact of basic attentional processes such as AR. Studies that measured reaction times toward stimuli exposed for prolonged durations (Bellocchi & Bastien-Toniazzo, 2007) might also confound results with speed of motor/behavioural engagement and the tendency to double-check perceptual accuracy in response to uncertainty. In addition, Martelli et al. (2009) found that crowding differences between typical and dyslexic readers became non-significant when given sufficient processing time (as is consistent with the AR efficiency hypothesis).

To address these methodological concerns, recent research with adults employed an orientation discrimination task using simple stimuli (Gabor sinusoids) presented for individually adjusted durations (Cassim, Talcott, & Moores, 2014; Moores, Cassim, & Talcott, 2011). Durations were adjusted based on accuracy rather than response time and were sensitive to within-experiment fluctuations by adding or subtracting 10 ms if accuracy dropped below 60% or rose above 90%, respectively. These conditions enabled each participant to express their optimal performance at all times while maintaining the shortest duration possible. Of all crowding research, these results are most likely to reflect true group attentional differences. Indeed, the RD group required longer durations than the control group. Even after compensating for processing time, accuracy of the RD group dropped substantially more than the control group from the uncrowded to the crowded condition. Again, the magnitude of performance drop was correlated with reading ability.

In conclusion, research to date continues to support abnormal crowding effects for struggling readers as first observed by Bouma and Legein (1977). Recent research replicating these findings using simple, non-linguistic stimuli bolsters the argument for an underlying AR deficit in RD crowding. This is not to say that deficient neural letter representations of letters and orthographies do not also contribute to crowding with letters in RD, as is most practically relevant for reading. Rather, AR efficiency is proposed to represent an additional and independent factor, among various other factors, that impairs letter and word processing in RD.

Development of Attention

Children are born with the capacity to use the same attentional processes as adults, including adjusting the grain of AR in response to environmental cues (this was observed in infants as young as 8 months old in Ronconi, Franchin, Valenza, Gori, & Facoetti, 2015). However, the extent and efficiency with which children employ these abilities improves with age and practice (Plude, Enns, & Brodeur, 1994). Notably, Jeon, Hamid, Maurer, and Lewis (2010) found that critical crowding distances (critical spacing) remained significantly wider for 5-, 8-, and 11-year-old children than for adults. In fact, developmental trajectories in crowding coincide closely with those of AR modulation abilities. In a pioneering study on the development of AR in typically developing children, Wolf and Pfeiffer (2014) employed a dot-tracking task in which the children had to follow the “robber” (target dot) as it moved among visually identical distractor dots. Target-distractor dot-pass distances were manipulated to control for AR precision demands (closer distances require more precise resolution). They found that AR precision increased incrementally between ages 7 through 13 and that the precision of 13-year-olds remained coarser than adult precision. AR development thus has a wide range of improvement protracted over an extended period of time.

There are two routes by which atypical patterns of AR development could impact children with RD. On one hand, AR deficiencies could be an inherent deficit in these children. In this case, AR deficits pre-exist exposure to reading and have a direct, causal impact on impaired emerging reading skills. Indeed, both phonological and visual-attentional abilities are abnormal in pre-reading children who are at-risk for dyslexia due to familial history of RD (Facoetti, Corradi, Ruffino, Gori, & Zorzi, 2010). Of primary interest to the current study is the second – although not mutually exclusive – route of reading impact whereby AR development coincides with reading experience and exposure to print (reading-exposure hypothesis). The introduction of reading instruction likely facilitates AR development by repeatedly engaging attentional processes in fine-grained resolution tasks. Children with RD read far less than their typically developing peers (Snowling, Muter, & Carroll, 2007; van Bergen et al., 2018) and thus gain less practice in making AR adjustments to the level of precision required for print processing.

The hypothesized experience-dependent route of AR development is consistent with research demonstrating that playing action video games enhances visuo-spatial resolution (Green & Bavelier, 2007) and improves reading performance (Franceschini et al., 2013). Importantly, action video games were shown to increase reading speed without decreasing decoding accuracy (Franceschini et al., 2013). Part of the effectiveness of action video game playing could be due to perceptual training opportunities that provide practice in making AR adjustments precisely and proficiently, thereby improving the efficiency of AR modulation during reading. This field of research has inspired a push toward including perceptual learning in reading interventions (Gori & Facoetti, 2014). Time spent reading and playing action video games were therefore both explored as part of the test of experienced-based perceptual learning in AR development.

The Current Study

The current study aimed to look at the efficiency of attention resolution (AR) in children of different ages and levels of reading ability. The methodology was modelled after Wolf and Pfeiffer (2014) who were successful in capturing age-based differences in AR precision modulation in typically developing children. Wolf and Pfeiffer’s AR task was adapted only slightly, making as few modifications as possible to accommodate the current study’s primary goal of exploring AR efficiency in struggling readers in the context of AR precision demands. The adaptations made to the AR task enabled this study to partially replicate Wolf and Pfeiffer’s results while extending their findings to include the influence of AR efficiency within AR processes at different stages of development.

The current study employed a cross-sectional design with children varying in reading ability in Grades 2 and 6 to examine age-based changes in AR efficiency as a function of reading ability and exposure to print and/or action video games. Participants completed a dot-tracking task in which they were asked to identify a target dot after tracking it in foveal vision as it moved among identical distractor dots. Trial conditions varied both in the distance (close, far) and speed (slow, fast) of target-distractor dot passes (as opposed to only varying distance as in Wolf and Pfeiffer). The premise underlying these manipulations is that closer dot-pass distances require greater AR precision, while faster dot-speeds reduce the time that children have to adjust AR to the level of precision needed to maintain focus on the target dot during dot-passes. Therefore, performance under different speed conditions is assumed to reflect relative efficiency in AR modulation. Grades 2 and 6 were chosen to represent distinct stages of AR development. Wolf and Pfeiffer found significant improvements from 7 to 9 years of age, and again from 9 to 11 years of age, while the 11-year-olds did not differ from 13-year-olds. Grade 2 children (7- to 8-year-olds) thus have relatively undeveloped AR, while Grade 6 children (11- to 12-year-olds) have reached a temporary plateau of AR development following a period of rapid growth. The two levels of distance chosen for this study were based on the distance thresholds identified by Wolf and Pfeiffer for children in Grade 2 (far distance condition) and for adults (close distance condition). Extremities in children's distance thresholds were chosen in order to test the limits of AR modulation abilities based on the added factor of AR efficiency. By comparing slow and fast trials at levels of AR precision previously identified as easy and difficult for children in the chosen age groups, the current study explored whether children are able to maintain good performance at a comfortable distance threshold when AR efficiency demands increase, and conversely, whether they can achieve even higher levels of AR precision than previously measured when AR efficiency demands are reduced. The comparison of each group's performance across the distance and speed conditions indicates how well children of different ages and reading abilities are able to meet AR precision demands as a function of AR efficiency. In addition, parent-report measures related to time spent reading and playing action video games were included to explore the role of perceptual experience in AR development. The relative importance of age and reading exposure on AR modulation ability was explored by comparing the Grade 6 struggling readers with a Grade 2 reading-age-matched control group.

Hypotheses

Better dot-tracking performance (higher AR accuracy) was expected in the far compared to the close distance condition (Hypothesis 1), the slow compared to the fast speed condition (Hypothesis 2), the Grade 6 children compared to the Grade 2 children (Hypothesis 3), and in better-able readers than in less-able readers (Hypothesis 4). Based on the AR efficiency hypothesis in struggling readers, the difference between typical and struggling readers was expected to be larger in the fast speed condition than the slow speed condition (Hypothesis 5). Based on the reading-exposure hypothesis of AR development, larger AR accuracy differences between struggling and non-struggling readers were expected in Grade 6 than in Grade 2 (Hypothesis 6). This prediction was based on the expectation that reading-ability-dependent differences in cumulative lifetime reading exposure will have been larger in the older children than in the younger children (due to reading aversion and poorer quality learning experiences in the struggling reader population). Therefore, larger reader group differences in AR accuracy in the older age group would support the hypothesis that AR modulation is practiced and improved through reading exposure. Alternately, if the gap between struggling and non-struggling readers is the same in Grades 2 and 6, results would point toward a general developmental delay in AR development compared to same-age peers. The experience-dependent-route of AR development was further explored by examining correlations between AR accuracy and parent estimates of children’s time spent reading and playing action video games, although correlation results are interpreted with caution given the unreliable nature of retrospective reports. As a final test of the tenability of the reading-exposure hypothesis, Grade 6 struggling readers were compared with a reading-age-matched control group in Grade 2. If these groups perform similarly on both reading and AR measures, it would suggest that AR development is more strongly related to reading ability (and by association reading exposure) than to chronological age.

In regard to the general influence of efficiency on AR development, it was hypothesized that children’s performance at different levels of AR precision (i.e., distance condition) would be differentially impacted by AR efficiency (i.e., speed condition), depending on grade level (Hypothesis 7). The performance of Grade 2 children was expected to be low in the close distance condition regardless of speed, given that the close distance (based on adult levels of AR precision) far exceeds the distance threshold for Grade 2 children. On the other hand, a large effect of speed was expected in the far distance condition, where performance was expected to be similar to that found by Wolf and Pfeiffer (75% accuracy) at this distance for children in this age group, but at the slow speed only (far-slow condition). As for the far-fast condition, comparable performance with the close distance condition (if close distance performance is uniformly low, as predicted) would support a vital role of efficiency in AR modulation skills by showing that increasing AR efficiency demands (fast speed) reduces performance in a similar way as increasing AR precision demands (close distance).

In Grade 6, performance was expected to be high in the far distance condition regardless of speed. Given that the close distance condition was based on adult levels of AR precision, performance was expected to be low in both speed conditions at the close distance; however, a significant difference between the slow speed and the fast speed would suggest that estimates on the limit of AR precision depend, in part, on AR efficiency.

The results inform how the visuo-attentional skill of AR modulation differs among children of varying reading abilities at different ages and how it may contribute to reading difficulties. The results also highlight the importance of AR efficiency when estimating developmental thresholds for AR precision.

Method

Participants

Participants included 244 children in Grades 2 and 6 recruited from nine public schools in Winnipeg, Manitoba. Children were initially nominated by their teachers as poor or average readers and were assigned post-hoc to one of three reader groups (below-average, average, above-average) based on their performance on a standardized measure of reading achievement (the TOWRE-2; see “Reading ability” under “Measures and Materials” for a description of the group assignment procedures). Participating parents or guardians provided written consent for their child’s involvement in the study (see Appendix A for the consent form) and completed a brief socio-demographic questionnaire (see Appendix B). Children provided verbal assent prior to testing and were assured that they could terminate their involvement in the study at any time.

A final sample of 201 children was selected for analyses from the 244 tested children based on the availability of outcome data on the AR task and after applying four sets of exclusionary criteria. In combination, exclusionary criteria identified 25 participants for exclusion; the remaining 18 excluded participants were missing data on the AR task. The first exclusionary criterion was a formal diagnosis of Attention-Deficit/Hyperactivity Disorder (ADHD; 11 exclusions), as identified by parents on the socio-demographic questionnaire. This criterion ensured that attention-related difficulties associated with ADHD did not have an impact on AR task results. The second exclusionary criterion, characterized as limited English language proficiency (14 exclusions), was included in order to ensure that participants were accurately assigned to the reader groups based on scores from an English reading measure (the TOWRE-2).

Limited English proficiency identification included two criteria, the first being parent responses to specific items on the socio-demographic questionnaire, and the second being children's below-average scores on a standardized measure of English vocabulary (the PPVT-4). On the socio-demographic questionnaire, parents of children with limited English proficiency indicated that *either* (a) the child is not fluent in English, or (b) English is not spoken in the home (as parents who do not speak English may not be able to accurately estimate their child's level of English proficiency). Of the children identified based on these questionnaire items, those who obtained a standard score of less than 90 (more than 1 *SD* below the mean) on the PPVT-4 were excluded from analyses. The third exclusionary criterion included limited intellectual ability to a degree that was sufficient to impair comprehension of task instructions (0 exclusions). Limited intellectual ability was indicated by scores of 2 *SD* or more below the mean on each of two measures of general intelligence (IQ), one estimating verbal IQ (the PPVT-4) and the other estimating nonverbal IQ (the Matrix Reasoning subtest of the WASI-II). The fourth exclusionary criterion ensured that all participants had normal or corrected-to-normal visual acuity. The visual acuity criterion was set at a Snellen fraction denominator (20/*x*, where an *x* of 20 is considered to be perfect vision) of 50 or worse (i.e., a higher value) on the Landolt C task (0 exclusions).

Of the 18 children who met all of the inclusion criteria but who were missing data for the AR task, three children in Grade 2 did not pass the practice trials (practice trials were completed prior to the experimental trials in order to ensure understanding of the AR task). The remaining 15 children passed the practice trials but did not complete all of the experimental trials. Children who declined to complete all of the experimental trials were as likely to be in Grade 2 ($n = 11$) as in Grade 6 ($n = 4$): χ^2 (1, $N = 216$) = 3.51, $p = .061$. They were equally distributed among the three reader groups (below-average: *n* = 4; average: *n* = 6; above-average: *n* = 4): χ^2 (2, *N* = 216) = 0.79, *p* = .675.[1]

Measures and Materials

Attention resolution. An adapted version of Wolf and Pfeiffer's (2014) dot-tracking task was custom-developed in C# as the primary outcome measure for this study. In each trial, participants tracked a target dot in foveal vision as it moved among seven identical distractor dots. In order to maintain children's interest, a narrative was developed in which participants were told that the dots were fireflies and that their task was to catch the "special" firefly (see Appendix C for the text of this narrative). To maintain motivation across trials, intermittent feedback was provided by displaying an animated cartoon jar of fireflies, along with a statement indicating the number of fireflies "caught" thus far ("You got # fireflies!") based on the number of accurate responses.

Difficulty in dot-tracking (reflecting AR demands) was manipulated by altering the minimum centre to-centre distance at which target and distractor dots passed one another (with accuracy providing an index of participant AR precision), as well as the speed at which the dots moved (with accuracy providing an index of participant AR efficiency). The two distance conditions were 3.5 and 8 arcmin (close, far). These distances were chosen based on children's upper and lower distance thresholds as estimated by Wolf and Pfeiffer, who found that children of all ages could track the dot with 75% accuracy at 8 arcmin. In comparison, only adults could track the dot with 75% accuracy at their tested distance of 3.3 arcmin. The minimum centre-to-centre distance between distractor dots was 6 arcmin in all trials. The two speed conditions, tested at each distance, included 0.645 cm/s and 2.2575 cm/s (slow, fast). Dot speed was the

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[1] One participant with missing data on the AR task was also missing data for the TOWRE-2, and could therefore not be assigned to a reader group for this analysis.

same for all dots and remained constant throughout each trial. Pilot testing demonstrated that the chosen distance and speed conditions were sensitive to age group differences (Zinger, Kruk, & Hildebrand, in preparation; see Appendix D for the abstract of the pilot study).

Trial sequence. Before each trial, a fixation area appeared on the laptop screen, comprised of a small black square (RGB[0 0 0], 27.4 cd/m²) with a side length of 0.81° visual angle in the center of a dark grey background filling the screen (RGB[30 30 30]; 51.8 cd/m²). This area remained on display until the experimenter commenced the trial. At the start of a trial, eight white round dots (RGB[200 200 200], 159cd/m²) with a diameter of 0.0112° visual angle (0.675 arcmin) appeared in random positions inside the black square and remained motionless for 1105 ms (65 frames of 17 ms each). Next, one dot was marked as the target dot over a period of 1972 ms with a flashing red circle (116 frames of 17 ms per each of six flashes). All dots remained static for an additional 340 ms (20 frames of 17 ms each) before beginning the movement sequence.

Each movement sequence lasted 7000 ms, after which the dots remained static in their final positions. Two dots were highlighted with an orange and blue circle, one circling the target and the other circling the distractor dot in closest proximity to the target. In half of the trials, the target was highlighted in orange, while in the other half the target was highlighted in blue. Trials of each type were randomly distributed throughout the task and the color of the target circle at the end of each movement sequence was counterbalanced across participants. Dots remained visible until participants verbally indicated which dot was the target dot by saying “blue” or “orange.” The experimenter entered children’s responses using a computer mouse. Participants were encouraged to guess if they were unsure and were permitted to change their responses if desired. The last-entered choice was recorded as the participant’s intended answer. Feedback on cumulative accuracy was given every six trials. See Figure 3 for a graphic depiction of trial stimuli and events.

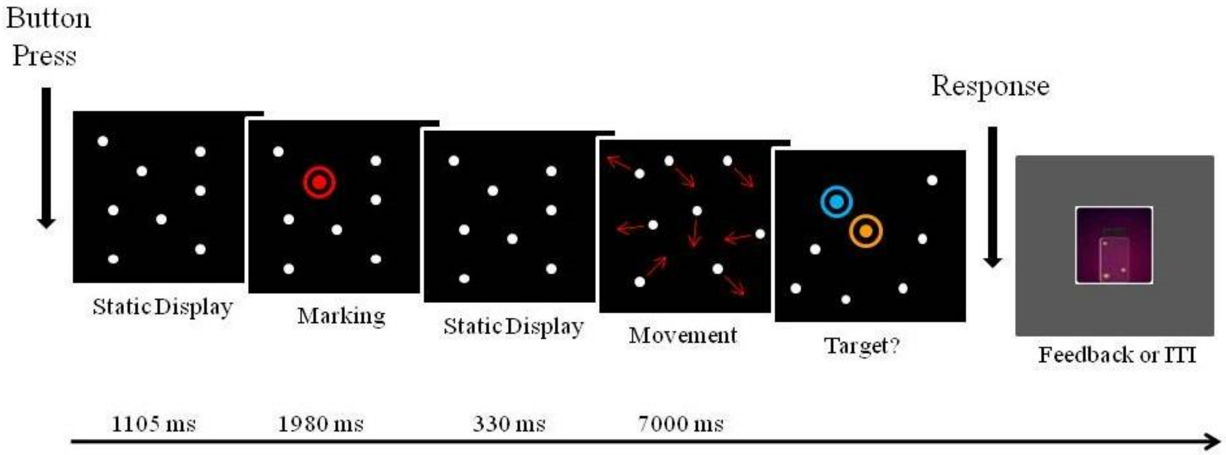

Figure 3. Sequence of trial events in the AR dot-tracking task.

Movement sequences were coded in advance using C# programming language to ensure that each sequence met specific criteria:

1. Number of passes: The target dot reached the minimum center-to-center distance with the distractor dots precisely six times within each trial.
2. Travel distance: The display square was divided into 36 equally sized and non-overlapping sections (in a 6 x 6 matrix of square areas), and the target dot passed through a minimum of 10 different sections.
3. Dot trajectories: All dots primarily followed linear pathways, navigating boundaries (walls, proximity to other dots) according to laws of reflection; however, the direction of movement changed with 10% probability every five frames to reduce the predictability of dot trajectories.

Twenty-three movement sequences meeting these criteria were generated for each Distance x Speed condition, resulting in 92 sequences. Twelve sequences per condition (48 in total) were selected based on visual inspection to ensure comparability of the trials within each condition on the travel distance of the target dot and its clustering with distractor dots.

Sequence of task events. The AR task proceeded through two phases including practice trials and experimental trials. To ensure understanding of the task, participants proceeded to the experimental trials only if they achieved four consecutive practice trials correct within 16 trials. Practice trials were made easier than experimental trials by reducing the number of distractor dots from seven to four and by increasing the minimum target-distractor pass distance from 6 to 10 arcmin. Feedback on accuracy was provided after every trial during the practice phase.

The 48 experimental trials were split into two blocks of 24 trials each with equal numbers of trials from each condition (including distance, speed, and target colour). Trials from all conditions appeared in randomized order to minimize practice effects, and the order of blocks were counterbalanced across participants. Participants were encouraged to blink between trials, and breaks were offered periodically (or as often as requested) to avoid strain on the eyes. The outcome measure was mean correct accuracy in each condition. The AR task took approximately 15 to 20 minutes to complete, including 5 minutes per block of trials plus individual times for instructions, practice trials, and breaks. Task reliability across all 48 trials was good, as assessed with Cronbach’s alpha (α = .83).

Reading ability.

Comprehensive Test of Phonological Processing-Second Edition (CTOPP-2). Phonological processing was assessed using the Elision and rapid naming subtests from the CTOPP-2 (Wagner et al., 2013). The Elision subtest measured the participants’ knowledge of, and ability to manipulate, the sound structure of spoken language. In each item, the researcher orally presented a word to the participant, who was first asked to repeat the word back to the researcher verbatim, and then with one specified phoneme missing (e.g. – say ‘star’; now say ‘star’ without the /s/). Scores reflect the number of correctly pronounced words with an absent phoneme out of a possible 34 words. The two rapid naming subtests measured speed in translating visual symbols into phonological code, which is highly predictive of reading fluency in children (Norton & Wolf, 2012). In each subtest, one printed page was presented containing four lines of six randomly ordered symbols (either letters or numbers). Each symbol was repeated six times for a total of 36 symbols per page (i.e., per subtest). Participants were asked to name all items on the page as quickly and accurately as possible, and scores reflect the time taken to name all items. Together, the Elision and rapid naming subtests took approximately 10 minutes to complete. Each subtest produced an age-normed scaled score with a population mean of 10 and standard deviation of 3. The scores selected for data analysis included the scaled subtest score for Elision (termed “phonological processing”) and a standard rapid naming composite score (*M* = 100, *SD* = 15) based on a direct linear transformation of the two rapid naming subtest scores. Coefficient alphas for Elision ranged from .92 to .93 for children ages 6 to 8 years, and from .87 to .92 for children ages 10 to 12 years. Corrected test-retest reliability coefficients for children ages 7 to 11 years were .77 for Elision and .89 for rapid naming; for children ages 12 to 18 years, the coefficients were .81 for Elision and .87 for rapid naming (Wagner et al., 2013).

Test of Word Reading Efficiency-Second Edition (TOWRE-2). The TOWRE-2 (Torgesen et al., 2012) is a commonly used reading achievement test that reliably differentiates between individuals with and without reading difficulties; test norms span the range from 6 to 24 years of age. The two time-limited subtests measured fluent decoding and pronunciation of 108 printed words (Sight Word Efficiency) and 66 phonemically regular nonwords (Phoneme

Decoding Efficiency). Sight words gradually decreased in frequency of occurrence and nonwords increased in complexity. A standard score (*M* = 100, *SD* = 15) was provided for each subtest based on the number of items pronounced accurately within 45 seconds. Reader group assignment procedures were based on a composite "reading efficiency" standard score based on a direct linear transformation of the two subtest scores. The TOWRE-2 took approximately five minutes to complete. Corrected test-retest reliability coefficients across the subtest and composite scores ranged from .86 to .93 for children 6 – 7 years of age and from .90 to .94 for children 8 – 12 years of age (Torgesen et al., 2012).

Reader group assignment. Reading efficiency composite standard scores on the TOWRE-2 were used to assign participants to reader groups. As per the interpretive guidelines provided by the TOWRE-2, participants who obtained a score of 90 or below were assigned to the below-average-reader (BA) group (this group corresponds to children previously referred to as "struggling readers"),[2] those who scored from 91 to 110 were assigned to the average-reader (AV) group, and those who scored 111 or above were assigned to the above-average-reader (AA) group. A 2 (grade) x 3 (reader group) between-subjects factorial ANOVA was conducted on the reading efficiency composite scores in order to confirm reader group differences on reading ability (indicated by a significant main effect of reader group), and to assess the comparability of reader groups across grades (indicated by a non-significant result for the effects involving grade). As expected, the main effect of reader group was highly significant, *F*(2, 195) = 582.57, *p* < .001, as were the Bonferroni-adjusted comparisons between all pairs of reader group combinations at the main effect level (*p*s < .001). In regard to cross-grade comparability, although the main effect of grade was not significant, *F*(1, 195) = 2.25, *p* = .135, the Grade x

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[2] The TOWRE-2 identifies the below-average group as beginning at a standard score of 89 or below. This criterion was changed by one point to a standard score of 90 in order to maintain similar sample sizes among the groups.

Reader Group interaction did just barely reach significance, *F*(2, 195) = 3.05, *p* = .050. Follow-up analyses for this interaction included simple main effects of grade within each level of the reader group variable. Results indicated that the effect of grade was significant for the below-average-readers, *t*(54) = -2,58, *p* = .01, but not for the average-readers, *t*(64) = 0.48, *p* = .631, or the above-average-readers, *t*(77) = 0.75, *p* = .456. For the below-average-readers, the Grade 6 sample (*M* = 81.37, *SD* = 6.43) scored higher than the Grade 2 sample (*M* = 76.72, *SD* = 9.28), even though the groups in both grades scored well below the cut-off score of 90. Overall, the analyses confirmed that the reader group assignment procedures successfully established groups of varying reading ability; however, the magnitude of reading impairment for the below-average-readers was larger in Grade 2 than in Grade 6 in the current sample. Cross-grade comparisons involving both groups of below-average-readers should therefore be interpreted with caution, particularly if comparing the influence of age versus reading ability on the results.

In the interest of establishing a reading-ability-matched comparison group for the Grade 6 below-average-readers, a planned independent samples *t*-test was conducted on the raw scores for the Sight Word Efficiency subtest of the TOWRE-2, comparing the Grade 6 below-average-readers (*M* = 61.31, *SD* = 5.62) and the Grade 2 above-average-readers (*M* = 62.76, *SD* = 5.94). The non-significant result, *t*(61) = .975, *p* = .334, confirmed that the two groups were matched on overall reading achievement despite their age difference, allowing for a reading-age-matched control comparison. By comparing children who were matched on reading ability but who differed in age, inferences could be made about the relative contributions of reading exposure and developmental maturation on AR efficiency differences between groups. Note that the mean raw score on the Phoneme Decoding Efficiency subtest of the TOWRE-2 and the Elision subtest of the CTOPP-2 remained higher for Grade 2 above-average-readers (Phoneme Decoding

Efficiency: *M* = 33.87, *SD* = 8.67; Elision: *M* = 26.05, *SD* = 6.03) than for Grade 6 below-average-readers (Phoneme Decoding Efficiency*:* *M* = 24.15, *SD* = 7.86; *p* < .001; Elision: *M* = 22.11, *SD* = 5.79, *p* = .011). Therefore, despite similar levels of word-reading achievement between groups, the Grade 6 below-average-readers showed poorer phonological processing skills compared to the above-average-readers in Grade 2. These groups did not differ on mean raw scores for either of the two rapid naming subtests (*p*s > .05).

Cognitive ability.

Peabody Picture Vocabulary Test-Fourth Edition (PPVT-4). The PPVT-4 (Dunn & Dunn, 2007) is a measure of receptive vocabulary knowledge and is commonly used as a proxy for verbal and/or overall intelligence (e.g., Tanaka et al., 2011) given its high correlations with full-scale IQ scores on other intelligence measures (Dunn & Dunn, 2007). Each item in the PPVT-4 presented four pictures to the participant at a time. The researcher presented one word orally, and participants were asked to select which one of the four pictures corresponded to the orally presented word. The PPVT-4 contained 228 items separated into sets of 12 items each. Successive sets of words increased in difficulty, corresponding to typical levels of vocabulary development at different ages. Participants completed all items in a set regardless of accuracy, beginning with the set corresponding to their chronological age. Sets were first completed in descending order until a minimum basal accuracy of 11 items was achieved, and then in ascending order until fewer than eight items in a set were answered correctly. Analyses used the age-normed standardized score (*M* = 100, *SD* = 15) based on total accuracy out of 228 items, where items from sets below the basal set were marked as correct and items from sets above the highest completed set were marked as incorrect. The PPVT-4 took approximately 15 minutes to complete. Split-half reliability and internal consistency coefficients for the PPVT-4 were .93 and above for the age groups in this study (Dunn & Dunn, 2007).

Wechsler Abbreviated Scale of Intelligence-Second Edition (WASI-II). Nonverbal cognitive ability was estimated using the Matrix Reasoning subtest of the WASI-II (Wechlser, 2011). In each of the 30 untimed items, children were shown an incomplete visual pattern and were asked to choose one out of five options that best fit the missing part of the pattern. This task captured fluid, nonverbal intelligence by means of several visual-spatial cognitive processes that are similar to those involved in the AR task, including perceptual organization and attention to whole-part relationships. Scores reflect the number of correctly completed matrices. Raw scores out of 30 were converted into *T* scores with a mean of 50 and standard deviation of 10. This subtest took approximately 5 minutes to complete. Split-half reliability coefficients for Matrix Reasoning exceeded .85 for children in the age groups involved in this study. The corrected test-retest coefficient was .81 for 6- to 11-year-olds and .76 for 12- to 16-year-olds (Wechlser, 2011).

Visual acuity. Visual acuity was measured using a standard computerized measure called the Landolt C. Each trial presented a circle with a gap on the top, bottom, left, or right. The size of the circle decreased after each correctly identified gap location until the participant detected the gap 75% of the time. A score of 20/50 visual acuity, either corrected or uncorrected, was required within a 95% confidence interval in order for a participants' data to be included in analyses. It typically took 30 trials (less than 5 minutes) to reach the minimum size.

In the current sample, 94.5% of participants (*n* = 190) obtained visual acuity scores of 20/20 or better ("normal" visual acuity group). Of the 11 participants who scored worse than 20/20 ("low" visual acuity group), the most extreme score was 20/33 in a Grade 2 average-reader. The other 10 "low" visual acuity scores were between 20/21 and 20/27, and were predominantly found in Grade 2 (*n* = 8; all reader groups), and in the Grade 6 below-average-readers (*n* = 2). Differences in performance on the AR task based on visual acuity were examined with a dichotomous variable that compared the “normal” and “low” visual acuity groups. Based on the results of this analysis (see “Influence of Sample Characteristics” below), the 11 participants with “low” visual acuity scores were kept in the analyses.

Demographic variables. Demographic information was collected from parents or guardians on the socio-demographic questionnaire (see Appendix B). The questionnaire included items regarding the child’s gender, age, relevant diagnoses (e.g., ADHD), and English fluency.[3] Given the importance of familiarity with the English language to the current study, parents were asked to list all language(s) spoken in the home and to indicate whether these included English only, English and another language, or another language only (hereafter referred to as non-English homes). Socio-economic status was estimated based on items regarding annual household income and parental education. Income was dichotomized as either high (≥ $50,000) or low (< $50,000). An annual household income of $50, 000 encompasses the Statistics Canada (2019) low-income cut-off salaries for city-based households of up to six persons after tax (or up to four persons before tax). For the parental education item, responses were coded as “1” if at least one parent identified themselves as having obtained a post-secondary degree, or as “0” if the highest level of education identified was no higher than a high school diploma.

On the questionnaire, parents were also asked to estimate the average number of minutes per week their child was currently spending reading for pleasure (reading exposure variable) and playing action video games (gaming exposure variable), as both of these factors were hypothesized to have an impact on AR development. Given that the estimates of reading

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[3] Additional items regarding handedness, number of siblings, and whether the child received previous help for reading were included on the questionnaire for another study in which a portion of participants also took part.

exposure and gaming exposure were retrospective, analyses of these data were completed on dichotomized variables based on a median split of the raw scores. High and low exposure groups were split based on the within-grade median for within-grade analyses in order to control for age-related differences in raw scores (e.g., parents may permit older children to spend more time playing video games than younger children). Groups were split based on the whole-sample median to compare levels of reading and gaming exposure across grades.

Procedure

Testing took place in children's schools. Rooms were requested in quiet areas and with controlled lighting (either without windows, or with blinds), and care was taken to keep testing environments across settings as similar as possible.

Paper-based reading and cognitive ability measures (TOWRE-2, CTOPP-2, and WASI-II: Matrix Reasoning) were administered in one block of activities. Computer-based tasks were administered in another block of activities (Landolt C, AR task, PPVT-4). The order of activity blocks were counterbalanced across participants. Children were asked for assent (see Appendix E for assent script), were invited to request breaks at any time, and were offered breaks between tasks as needed and between each block of trials in the AR task.

Following testing, the researcher rated how distracted the child was on each task on a 5-point Likert scale (1 = *not at all distracted*, 5 = *very distracted*); however, these ratings had limited reliability because they relied on multiple different rater's subjective evaluations of children's observable behaviour. It is possible that each rater held different internal criteria for evaluating behavioural signs of distraction. Furthermore, distractibility ratings were missing for a significant number of participants, including 14 participants from the final sample on the AR task. Distractibility ratings were therefore not examined in statistical analyses. The impact of attentional deficits on the results was primarily controlled through the exclusion of participants with a formal diagnosis of ADHD.

Stimuli were displayed on a Dell Precision M7600 laptop computer, with a 15.6-inch ultra-high-resolution LCD screen (3840 X 2160), 60 Hz refresh rate, and an Intel Core i7-6820HQ processor. The display driver was an NVIDIA Quadro M2000. Participants sat 2.2 meters from the screen in order to ensure that the stimuli subtended the required visual angle to provide the appropriate test of AR precision and efficiency. Children were reminded to lean directly against the back of the chair as needed.

Assessment of Parametric Statistical Assumptions

The following procedures were used to assess all continuous quantitative measures for the assumptions of parametric statistics which include normality, homogeneity of variance, and an absence of influential outliers. Distributions were flagged as potentially non-normal whenever skewness or kurtosis values exceeded ± 2 (George and Mallery, 2001). Flagged distributions were subsequently determined to be non-normal if congruent conclusions could be drawn based on (1) visual inspection of histograms and Q-Q plots and (2) comparison of the skewness/kurtosis *z*-score (skewness or kurtosis statistic divided by its standard error) against a significance level of $p = .01$ (critical *z*-score of 2.58; Laerd Statistics, 2018a). Homogeneity of variance was assessed using Levene’s test, where a significant result was further assessed using Hartley’s F_{Max}. The assumption of homogeneity of variance was considered to be violated if the variance ratio for the flagged variable (largest group variance divided by the smallest group variance) exceeded a critical F_{Max} value, as determined by the sample size and number of compared variances. Outliers were assessed based on visual inspection of boxplots, where distributions were flagged based on the number and severity of outlying scores.

When analyzing continuous measures found to violate one or more of these statistical assumptions in at least one of the tested groups, parametric test results were verified using a robust non-parametric test, when available. Non-parametric tests based on mean ranks were chosen for verification analyses, including the Mann-Whitney *U* test for comparisons of two independent samples, the Kruskal-Wallis *H* test for comparisons of three or more independent samples, and the Related-Samples Wilcoxon Signed Rank Test for comparisons of paired within-subjects conditions. These tests rank the raw scores on the outcome measure in ascending order, and determine if the majority of scores in each group are ranked higher (or lower) than the majority of scores in the other group(s), based on the mean rankings of scores within each group.[4] These non-parametric tests were also used to analyze non-continuous variables (e.g., reading exposure, gaming exposure).

Assumption violations were identified in the following quantitative background measures: reading efficiency (TOWRE-2 composite), Sight Word Efficiency (TOWRE-2 subtest), phonological processing (CTOPP-2: Elision subtest), and rapid naming (CTOPP-2 composite). For reading efficiency and rapid naming, assumption violations were identified in Grade 6 but not in Grade 2. The remaining continuous variables met the assumptions for parametric statistics, including Phoneme Decoding Efficiency (TOWRE-2 subtest), verbal IQ (PPVT-4), and nonverbal IQ (WASI-II: Matrix Reasoning subtest). The assumption test results for the AR task data are provided below under “Statistical properties of AR sensitivity scores”.

Non-parametric verification tests are discussed in the results only when the outcome is incongruent with that obtained from the associated parametric test. Otherwise, results are reported based on parametric test statistics regardless of underlying assumption violations.

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[4] When the distributions are similar in shape across groups, ranked-score tests can also be interpreted as a test of medians; however, the similarity of group distributions can only be assessed subjectively based on visual inspection of boxplots. The current results are therefore interpreted based on mean ranks throughout.

Results

Sample Characteristics

Demographic variables. A summary of the demographic characteristics of each reader group in each grade is presented in Table 1. Demographic information was provided by a subset of parents for each item on the socio-demographic questionnaire, and the number of missing cases is listed where applicable. Responses to the item asking about home language(s) indicated that English (n = 156) was the predominant language spoken in the homes, followed by Tagalog (n = 33). Thirty-five parents identified their homes as non-English homes, and 17 (48.6%) of these provided qualitative information on the other language spoken at home. The languages listed from non-English homes included Tagalog, Acholi, Punjabi, Amharic, Arabic, Spanish, Korean, and Krio. As noted, exclusionary criteria for the study required a minimum score of 90 on the PPVT-4 for participants from non-English homes in order to ensure acceptable familiarity with the English language (see “Participants” above).

One-way ANOVA assessed for age differences (in months) among the reader groups separately at each grade level. Significant reader group age differences emerged in Grade 2, $F(2, 94) = 9.39$, $p < .001$, and in Grade 6, $F(2,101) = 3.41$, $p = .037$. Bonferonni-adjusted pairwise comparisons found that within Grade 2, the below-average-readers were significantly older than the average-readers, $t(58) = 2.90$, $p = .014$, and the above-average-readers, $t(64) = 4.27$, $p < .001$; the latter two groups did not differ, $t(66) = 1.27$, $p = .617$. Within Grade 6, the below-average-readers were younger than the above-average-readers, $t(60) = -2.49$, $p = .043$, and neither of these groups differed in age from the average-readers: below-average: $t(60) = -2.09$, $p = .116$; above-average: $t(75) = -0.35$, $p = 1.00$.

Chi-square analyses assessed for differences between grades and among reader groups on

Table 1

Socio-Demographic Characteristics of the Reader Groups in Grade 2 and Grade 6

	Grade 2			Grade 6		
Variable	Below-average	Average	Above-average	Below-average	Average	Above-average
Total (male)	29 (13)	31 (11)	37 (19)	27 (11)	35 (14)	42 (22)
Mean age[a] (*SD*)	92.66 (3.35)	90.03 (3.72)	88.95 (3.42)	136.78 (5.0)	138.94 (3.83)	139.26 (3.48)
Income[b]	4 (13.8 %)	13 (41.9 %)	18 (48.6 %)	6 (22.2 %)	16 (45.7 %)	26 (61.9 %)
Missing	3	2	2	3	3	1
Parental education[c]	14 (48.3 %)	17 (54.8 %)	31 (83.8 %)	14 (51.9 %)	21 (60.0 %)	35 (83.3 %)
Missing	1	1	1	3	4	0
English fluency	25 (86.2 %)	28 (90.3 %)	36 (97.3 %)	26 (96.3 %)	32 (91.4 %)	42 (100 %)
Missing	2	1	0	1	0	0
Home language[d]	89.66 %	83.87 %	78.38 %	85.19%	62.86%	71.43 %
English	18	20	16	19	12	17
Other	1	3	7	3	12	9
Both	8	6	13	4	10	13
Missing	2	2	1	1	1	3

Note. Data provided by parents on the socio-demographic questionnaire. The unit of measurement is frequency of occurrence (*N*) unless otherwise specified. [a]Unit of measurement is in months. [b]Number of households with an annual income ≥ $50,000. [c]Number of households in which at least one parent obtained a post-secondary degree. [d]Percentage of households in which English was included as at least one of the home languages (English + Both/Total).

categorical demographic variables, including child gender (gender: male/female), child English fluency (English fluency: yes/no), annual household income (income: high/low), post-secondary parental education (parental education: yes/no), and whether English was spoken in the home (home language: English/non-English). To assess home language, households in which English was the only language spoken were grouped with households in which both English and another language were spoken. The proportion of these collective English-language households to the number of non-English households was compared across grades and across reader groups.

Significant group differences emerged among the reader groups on income, χ^2 (2, N = 187) = 17.91, $p < .001$, and parental education, χ^2 (2, N = 191) = 15.79, $p < .001$. The annual household income was listed as high (≥ $50,000) in 20.0% of below-average households, 47.5% of average- households, and 57.9% of above-average households. The percentage of children whose parent(s) completed post-secondary education was 53.8% for the below-average-reader group, 62.3% for the average-reader group, and 84.6% for the above-average-reader group. Analyses on home language revealed a significant difference between grade levels, χ^2 (1, N = 191) = 4.81, $p = .028$, and a marginal difference among reader groups, χ^2 (2, N = 191) = 5.83, $p = .054$. Eighty-eight percent of Grade 2 households spoke English in the home compared to 75.8% of Grade 6 households. Among the reader groups, 92.5% of below-average households spoke English in the home compared to 76.2% of average households and 78.7% of above-average households. The impact of the identified demographic variables found to differ among the groups (reader group: age, income, parental education; grade: home language) on the results is discussed below under “Influence of Sample Characteristics”.

Quantitative background measures. Group means and standard deviations for the quantitative background measures are presented in Table 2. The results of the analyses on group differences on these variables are summarized in Table 3.

Analyses between grades revealed that the mean Phoneme Decoding Efficiency subtest score was higher in Grade 6 than in Grade 2. The mean rapid naming composite score was higher in Grade 2 compared to Grade 6, although this result was only marginally significant using the non-parametric Mann-Whitney *U* test, $U = 4240.00$, $z = -1.96$, $p = .050$, which was completed for verification purposes due to assumption violations for parametric analysis in the rapid naming score distributions. For gaming exposure (whole-sample median split), the mean ranks of scores were higher in Grade 2 than in Grade 6 (i.e., the majority of scores in Grade 2 were higher than those in Grade 6).

Reader group analyses in Grades 2 and 6 revealed the expected group differences on reading-related measures, including reading efficiency (composite and subtests), phonological processing, and rapid naming, thus validating the make-up of the groups. Bonferroni-adjusted comparisons were significant among all reader groups in Grades 2 and 6 for reading efficiency and phonological processing, with the better-able reader group in each comparison-pair scoring higher than less-able reader group. For rapid naming, there was no difference between the below-average-readers and average-readers in either grade, and each of these groups scored lower, on average, in comparison to the grade-matched above-average-readers. There were no differences among the reader groups in either grade on gaming exposure, or among the reader groups in Grade 2 on reading exposure. In Grade 6, the below-average-readers were ranked lower on reading exposure than the other two reader groups, who did not differ.

Reader group differences were also found for verbal IQ and nonverbal IQ in both grades. Bonferonni-corrected comparisons among the reader groups in Grade 2 and Grade 6 found no difference between below-average-readers and average-readers, but significantly lower scores in

Table 2

Descriptive Statistics on Quantitative Background Measures by Grade and Reader Group

	Grade 2			Grade 6		
Measure Subtest	Below-average *M (SD)*	Average *M (SD)*	Above-average *M (SD)*	Below-average *M (SD)*	Average *M (SD)*	Above-average *M (SD)*
Visual acuity[a]	13.0 (4.79)	13.19 (4.96)	14.22 (4.47)	13.78 (3.97)	11.91 (2.59)	11.81 (2.33)
Verbal IQ[b]	94.21 (10.21)	99.03 (9.31)	110.43 (11.58)	92.85 (11.29)	99.26 (9.98)	109.62 (11.29)
Nonverbal IQ[c]	41.18 (6.33)	48.77 (6.92)	52.46 (8.01)	42.70 (8.11)	48.80 (9.37)	50.88 (10.02)
Reading efficiency[d]	76.72 (9.28)	100.77 (5.61)	119.70 (6.03)	81.37 (6.43)	101.57 (6.18)	118.57 (6.56)
Sight Word Efficiency[e]	79.07 (9.86)	104.16 (7.29)	117.87 (18.76)	81.41 (13.92)	99.54 (7.09)	116.10 (9.0)
Phoneme decoding[e]	76.76 (10.76)	97.55 (7.94)	116.73 (7.71)	80.70 (9.27)	103.37 (7.67)	119.0 (7.31)
Phonological processing[f]	6.76 (2.43)	9.81 (2.46)	12.41 (2.45)	7.19 (2.45)	10.17 (2.51)	11.64 (2.58)
Rapid naming[g]	94.48 (9.87)	100.13 (9.23)	107.41 (8.89)	84.22 (10.41)	93.49 (20.59)	105.17 (17.28)
Reading exposure[h]	198.59 (275.43)	119.45 (77.81)	189.03 (168.46)	112.50 (110.10)	159.86 (113.46)	227.31 (275.63)
Gaming exposure[h]	328.97 (786.43)	226.26 (242.95)	299.11 (242.56)	393.70 (585.03)	358.54 (498.01)	472.62 (451.15)

[a] Snellen fraction denominator (20/*x*) as measured on the Landolt C. A value of 20 or lower indicates average or better-than-average visual acuity. [b] PPVT-4: standard score. [c] WASI-II: Matrix Reasoning subtest, *T*-score. Missing data for one below-average-reader. [d] TOWRE-2: composite standard score. [e] TOWRE-2 subtest standard score. [f] CTOPP-2: Elision subtest scaled score. [g] CTOPP-2: composite standard score. [h] Socio-demographic questionnaire items on time spent reading for pleasure and time spent playing action video games. The unit of measurement is raw scores in minutes per week.

Table 3

Grade and Reader Group Differences on Continuous (Top) and Non-Continuous (Bottom) Background Measures

	Continuous Measures							
	Grade		Reader group (Grade 2)			Reader group (Grade 6)		
Measure Subtest	*F*	*p*	*F*	*p*	Adj. Pairwise Comparisons[h]	*F*	*p*	Adj. Pairwise Comparisons[h]
Verbal IQ[a]	0.01	.929	21.19	< .001	BA=AV<AA	20.99	< .001	BA=AV<AA
Nonverbal IQ[b]	0.004	.952	19.82	< .001	BA<AV=AA	6.46	.002	BA<AV=AA
Reading efficiency[d]	0.92	.338	302.56	< .001	BA<AV<AA	279.05	< .001	BA<AV<AA
Sight Word Efficiency[c]	0.02	.891	68.33	< .001	BA<AV<AA	100.28	< .001	BA<AV<AA
Phoneme decoding[c]	4.15	.043	168.23	< .001	BA<AV<AA	189.50	< .001	BA<AV<AA
Phonological processing[e]	0.05	.819	43.30	< .001	BA<AV<AA	25.72	< .001	BA<AV<AA
Rapid naming[f]	6.13	.014	16.02	< .001	BA=AV<AA	12.83	< .001	BA=AV<AA

	Non-Continuous Measures							
	Grade		Reader group (Grade 2)			Reader group (Grade 6)		
Measure	*H*	*p*	*H*	*p*	Adj. Pairwise Comparisons[h]	*H*	*p*	Adj. Pairwise Comparisons[h]
Reading exposure[g]	0.23	.631	2.90	.235	n/a	6.68	.035	BA<AV=AA
Gaming exposure[g]	6.80	.009	4.12	.128	n/a	2.32	.313	n/a

Note. Continuous measures were analyzed using one-way ANOVA. Non-continuous measures were analyzed using the Kruskal-Wallis *H* test.

[a] PPVT-4: standard score. [b] WASI-II: Matrix Reasoning subtest, *T* score. Missing data for one below-average-reader in Grade 2. [c] TOWRE-2: subtest standard score. [d] TOWRE-2: composite standard score. [e] CTOPP-2: Elision subtest scaled score. [f] CTOPP-2: composite standard score. [g] Raw scores on the socio-demographic questionnaire items for time spent reading for pleasure and time spent playing action video games were dichotomized based on a whole-sample (grade comparison) or within-grade (reader group comparisons) median-split. Raw scores were measured in minutes per week. [h] Bonferonni-adjusted pairwise comparisons among the below-average (BA), average (AV), and above-average (AA) reader groups.

each of these groups compared to the above-average-reader group in each grade. For nonverbal IQ, the below-average-reader group in each grade scored lower than the grade-matched average-reader group. Neither of the average-reader groups differed from the above-average-reader groups on nonverbal IQ. The reader group differences on measures of IQ were less expected than those on reading-related measures; however, prior research indicates that children with reading disabilities commonly score lower than their non-reading-disabled peers, despite having at least average intellectual abilities (Kudo, Lussier, & Swanson, 2015). Indeed, mean verbal IQ and nonverbal IQ scores were in the average range for both below-average-reader groups in the current sample. Any potential influences of IQ differences on the AR results can therefore be expected to generalize to the larger population of struggling readers. Existing literature on the analysis of data from groups with pre-existing neuro-developmental differences (e.g., learning disabilities) argues strongly against covarying out variability from condition-related differences in analyses (Dennis et al., 2009; Miller & Chapman, 2001). IQ measures were therefore not entered as covariates in the analysis of AR task data. Instead, an exploratory regression analysis examined the relationship between AR outcomes and meaningful characteristics of the struggling reader population, including IQ and specific reading processes (see “Exploratory Analyses on Predictors of Attention Resolution Sensitivity” below).

Attention Resolution Data Preparation

Descriptive statistics. Descriptive statistics on group AR accuracy scores (proportion of items correct) on the AR task are presented in Table 4 for each Distance x Speed condition.

Assessment of response bias. Prior to checking the AR data for violations of statistical assumptions, AR accuracy scores were assessed for response bias by comparing trials on which the target was highlighted in blue to trials on which the target was highlighted in orange. Target

Table 4

Descriptive Statistics on AR Accuracy and AR Sensitivity (Original and Winsorized) by Grade, Reader Group, and Condition

	Grade 2					
	Below-average		Average		Above-average	
	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)
Close-slow	.62 (.17)	0.66 (0.92)	.69 (.17)	1.08 (0.97)	.73 (.17)	1.27 (0.96)
Close-fast	.51 (.13)	0.07 (0.73)	.55 (.10)	0.26 (0.55)	.55 (.13)	0.32 (0.70)
Winsorized	—	—	—	*0.24 (0.50)*	—	—
Far-slow	.71 (.17)	1.19 (0.96)	.68 (.17)	1.03 (0.97)	.80 (.15)	1.67 (0.81)
Far-fast	.66 (.19)	0.87 (1.03)	.66 (.13)	0.89 (0.77)	.65 (.17)	1.84 (0.95)
	Grade 6					
	Below-average		Average		Above-average	
	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)	AR accuracy[a] (*M*, *SD*)	AR sensitivity[b] (*M*, *SD*)
Close-slow	.83 (.14)	1.86 (0.80)	.93 (.10)	2.40 (0.56)	.93 (.10)	2.38 (0.57)
Winsorized	—	—	—	*2.48 (0.38)*	—	*2.45 (0.35)*
Close-fast	.58 (.16)	0.48 (0.92)	.67 (.17)	0.94 (0.93)	.69 (.17)	1.05 (0.92)
Far-slow	.89 (.17)	2.17 (0.92)	.98 (.06)	2.65 (0.32)	.96 (.08)	2.55 (0.46)
Winsorized	—	*2.25 (0.71)*	—	*2.71 (0.15)*	—	*2.59 (0.30)*
Far-fast	.81 (.19)	1.71 (1.05)	.88 (.14)	2.10 (0.78)	.89 (.14)	2.18 (0.77)
Winsorized	—	*1.77 (0.91)*	—	*2.14 (0.64)*	—	*2.20 (0.69)*

Note. Winsorized statistics were only obtained on AR sensitivity scores in a subset of conditions, and within those conditions only in groups with outlying scores. Dashes appear in place of empty cells for AR accuracy and for AR sensitivity in groups without outlying scores per applicable condition.

[a]Measured in units of proportion correct out of 12 trials per condition where a score of .5 indicates chance performance. [b]Measured in standard deviation units (*d*') where a score of 0 indicates chance performance.

colour was found to significantly impact accuracy on the task, potentially indicating a tendency for participants to favour one colour over another (see Appendix F for a summary of the results of this analysis). In order to minimize the potential influence of response bias on the results, AR accuracy scores were adjusted using formulas derived from signal detection theory to reflect AR sensitivity instead of pure accuracy based on proportion correct (Stanislaw & Todorov, 1999). The target-marker color *blue* was arbitrarily selected such that when the target dot was highlighted in blue, an accurate “blue” response was called a “hit”. In contrast, when the target dot was highlighted in orange, an inaccurate “blue” response was called a “false alarm”. The false alarms and hits were converted into *z*-scores (using the PROBIT function in SPSS, as described in Stanislaw & Todorov, 1999), and the *z*-scores were subtracted to compute *d’* sensitivity. This was done for each within-subjects condition. The resulting *d’* scores (AR-d) represent the degree to which participants’ average AR sensitivity in each Distance x Speed condition differed from chance performance after adjusting the scores for response bias toward target colour in that condition. Values are presented in *z*-score units where a score of 0 indicates chance performance.

Statistical properties of AR sensitivity scores. AR-d scores were assessed for outliers, normality, and homogeneity of variance using the procedures described in the Method section under “Assessment of Parametric Statistical Assumptions”. The numbers of outliers identified per group and condition are summarized in Table 5. In Grade 2, the two outliers identified in the average-reader group in the close-fast condition were at the high end of the distribution, indicating higher AR sensitivity scores compared to the group. In Grade 6, outliers were identified in all conditions except for the close-fast condition. All Grade 6 outliers were at the low end of the distribution, indicating lower AR sensitivity in comparison to the group.

Table 5

Number of AR Sensitivity Score Outliers by Group and Condition

	Grade 2			Grade 6		
Condition	BA	AV	AA	BA	AV	AA
Close-slow	0	0	0	0	5	3
Close-fast	0	2	0	0	0	0
Far-slow	0	0	0	2	5	2
Far-fast	0	0	0	1	1	1

Note. BA = below-average-readers, AV = average-readers, AA = above-average-readers.

Non-normal distributions were observed in specific conditions for specific groups (skewness and kurtosis statistics are presented in Table 6). Notably, the Grade 6 groups tended toward negatively skewed and leptokurtic (positive kurtosis values) distributions in the easier Distance x Speed conditions, reflecting tall and slender curves (low variability) at higher levels of AR sensitivity. These conditions included both of the far distance conditions for the Grade 6 average-readers, and, in addition to these conditions, the close-slow condition for the Grade 6 above-average-readers. The distribution for Grade 6 below-average-readers was also leptokurtic in the far-slow condition, indicating slightly reduced variability than would be expected under a normal distribution despite acceptable skewness. All of the skewness and kurtosis values that exceeded ±2 were statistically significant at the p = .01 level, as indicated by their z-scores being greater than 2.58. Only the most difficult condition (close-fast) maintained acceptable skewness and kurtosis values for all groups. This pattern of results is understandable, given that the easier conditions are well within the predicted levels of AR modulation ability for the older children, thus producing near-ceiling effects. The impact of negatively skewed distributions in the higher performing groups and conditions is for scores in the negative tail of those distributions to diminish estimates of overall group performance, potentially increasing the likelihood of a Type II error using inferential statistics.

Table 6

Skewness and Kurtosis Statistics for Original and Winsorized AR Sensitivity Scores by Grade, Reader Group, and Condition

	Grade 2					
	Below-average		Average		Above-average	
	Skewness (*SE*)	Kurtosis (*SE*)	Skewness (*SE*)	Kurtosis (*SE*)	Skewness (*SE*)	Kurtosis (*SE*)
Close-slow	-0.11 (0.43)	-0.93 (0.85)	0.06 (0.42)	-0.90 (0.82)	-0.12 (0.39)	-0.67 (0.76)
Close-fast	0.22 (0.43)	-0.85 (0.85)	0.44 (0.42)	-0.69 (0.82)	-0.20 (0.39)	-0.29 (0.76)
Winsorized	—	—	*0.22 (0.43)*	*-0.85 (0.85)*	—	—
Far-slow	-0.53 (0.43)	-0.80 (0.85)	-0.23 (0.42)	-1.33 (0.82)	-0.28 (0.39)	-1.09 (0.76)
Far-fast	-0.28 (0.43)	-0.44 (0.85)	0.04 (0.42)	-0.77 (0.82)	-0.35 (0.39)	-0.18 (0.76)
	Grade 6					
	Below-average		Average		Above-average	
	Skewness (*SE*)	Kurtosis (*SE*)	Skewness (*SE*)	Kurtosis (*SE*)	Skewness (*SE*)	Kurtosis (*SE*)
Close-slow	-0.75 (0.45)	-0.23 (0.87)	-1.49 (0.40)	1.09 (0.78)	-2.41 (0.37)	7.21 (0.72)
Winsorized	—	—	*0.93 (0.40)*	*-0.70 (0.78)*	*-0.72 (0.37)*	*-0.80 (0.72)*
Close-fast	-0.07 (0.45)	-0.49 (0.87)	0.03 (0.40)	-0.92 (0.78)	-0.23 (0.37)	-0.88 (0.72)
Far-slow	-1.86 (.45)	3.47 (0.87)	-2.97 (0.40)	8.55 (0.78)	-3.11 (0.37)	11.56 (0.72)
Winsorized	*-1.10 (.45)*	*-0.31 (0.87)*	*-2.13 (0.40)*	*2.71 (0.78)*	*-1.58 (0.37)*	*1.47 (0.72)*
Far-fast	-1.15 (.448)	1.42 (0.87)	-2.16 (0.40)	6.41 (0.78)	-1.73 (0.37)	3.18 (0.72)
Winsorized	*-0.54 (.448)*	*-0.92 (0.87)*	*-1.20 (0.40)*	*1.29 (0.78)*	*-1.31 (0.37)*	*1.03 (0.72)*

Note. Winsorized statistics were obtained in only a subset of conditions, and within those conditions only in groups with outlying scores. Dashes appear in place of empty cells for groups without outlying scores per applicable condition.

The assessment of homogeneity of variance using Levene's test identified unequal variances among the groups for the conditions close-slow, $F(5, 195) = 6.29$, $p < .001$, close-fast, $F(5, 195) = 3.04$, $p = .012$, and far-slow, $F(5, 195) = 14.92$, $p < .001$, but not for the far-fast condition, $F(5, 195) = 1.79$, $p = .117$. The same pattern of results was confirmed with Hartley's F_{Max} using a critical F_{Max} value based on 30 participants per group.

In response to the abovementioned violations of statistical assumptions found in the data – including outliers, non-normality, and heterogeneity of variance – transformations were performed on the AR-d scores in succession of increasing severity, in an attempt to establish normal distributions across groups and conditions. A benefit of data transformations is that extreme scores are typically adjusted to a greater degree than scores closer to the mean, with the potential to address problems associated with outliers, normality, and heterogeneous variance simultaneously. Performed transformations included square root, logarithmic, and inverse transformations. Each transformation included reversal of the negative skew and centering at a minimum value of 1. None of the transformations were successful in establishing normality across groups and conditions; however, this outcome was not unexpected given the known difficulties associated with correcting for non-normality in distributions with heavy tails and outliers (Bradley, 1984; Osborne, 2013), such as those present in the current data set, using transformations.

Data analyses were therefore carried out on the original AR-d scores without adjustment or transformation; however, a comparison analysis was also performed using Winsorized sample means in order to verify the results using data with improved adherence to the statistical assumptions for parametric tests. Winsorized means were only calculated for conditions with outliers by replacing outlier values with the next-most-extreme score in the remaining sample.

The two high outliers in Grade 2 were therefore replaced with the next highest value, and the low outliers in Grade 6 were replaced with the next lowest value. This procedure of Winsorizing outliers only – as opposed to the typical Winsorization procedure in which a proportion of scores (e.g., 5%) is trimmed at both tails of the distribution – was adopted because the ceiling effects in some of the Grade 6 groups resulted in an absence of tails at the high ends of those distributions from which to trim scores.

Winsorized means and standard deviations are provided in Table 4 on separate rows directly beneath the non-Winsorized statistics of the corresponding cells. The impact of Winsorization on the group means was to adjust them in the direction of the majority of scores within the cell (toward the median), which arguably makes the Winsorized means more representative of group performance than the non-Winsorized means.

Skewness and kurtosis statistics on the Winsorized distributions are provided in Table 6 beneath those of the corresponding non-Winsorized distributions. These statistics show that Winsorization had the intended effect of improving skewness and kurtosis in all distributions, with only one cell still having values exceeding ± 2 (the far-slow condition for the Grade 6 average-readers). A visual inspection of boxplots confirmed that the Winsorized distributions were free from outliers with the exception of the Grade 6 average-reader distribution for the far-slow condition. Particularly strong ceiling effects emerged in this cell, such that any score corresponding to less than perfect performance was identified as an outlier. Winsorizing the outliers in this condition for a second time would have produced uniformly perfect scores. Winsorization was therefore terminated after the first adjustment, despite the fact that the same five outliers remained in this cell as were present prior to Winsorization.

In sum, Winsorization was successful in producing distributions that more closely adhered to the assumptions for parametric statistics; however, due to some remaining violations in these distributions, Winsorized means were used for comparative purposes only.

Primary Data Analysis

The primary analysis of AR sensitivity was a 2 x 3 x 2 x 2 mixed factorial ANOVA on non-Winsorized AR-d scores, with two between-subjects factors (grade, reader group) and two within-subjects factors (distance, speed). A comparative analysis of the same design using Winsorized means in place of non-Winsorized AR-d scores obtained results of the same pattern and strength as the primary analysis. Results are therefore only reported for the primary, non-Winsorized analysis; however, due to the violations of parametric statistical assumptions in these data, additional measures were taken to minimize their impact on the interpretation of the results. Significant effects were individually assessed for statistical assumptions based on the marginal means for that effect (i.e., means based on averaged scores across multiple cells of the design). When violations were identified in the marginal means of a significant effect, the results of follow-up tests of interest were verified using non-parametric tests. The pattern of results using non-parametric follow-up tests was no different than the results obtained using parametric tests. The results are therefore reported based on the parametric test statistics.

The combination of completing a comparative analysis using Winsorized means, assessing the statistical assumptions of the marginal means for significant effects, and verifying the results of planned comparisons using non-parametric tests, is believed to provide adequate support for a preliminary interpretation of the results, despite the noted violations of statistical assumptions in the data. Future studies would do well to verify these results using robust statistical procedures, such as those outlined by Wilcox (2005).

Effect sizes are reported in partial eta squared (ηp^2), an alternative effect size measure to eta squared (η^2) that, unlike eta squared, is not sensitive to the number and significance of other independent variables in the design. Partial eta squared is therefore recommended in factorial ANOVA designs because it is less likely to underestimate effects compared to eta squared (Cohen, 1973; Tabachnick & Fidell, 2013). Effect sizes were evaluated using the guidelines for experimental psychology research by Cohen (1988) for small ($\eta^2 = .01$), medium ($\eta^2 = .09$), and large ($\eta^2 = .25$) effects. All results are interpreted based on two-tailed *p*-values.

Overview of significant effects (Hypotheses 1 through 4). Significant main effects emerged for all factors, supporting Hypotheses 1 through 4. AR sensitivity was significantly better in the far distance condition ($M = 1.65$, $SE = 0.05$) than the close distance condition ($M = 1.07$, $SE = 0.05$), $F(1, 195) = 132.04$, $p < .001$, $\eta\text{p}^2 = .40$, and in the slow speed condition ($M = 1.74$, $SE = 0.05$) than the fast speed condition ($M = 0.98$, $SE = 0.05$), $F(1, 195) = 262.74$, $p < .001$, $\eta\text{p}^2 = .57$, confirming that the distance and speed manipulations effectively influenced performance in the expected directions. AR sensitivity was better in the Grade 6 group ($M = 1.87$, $SE = .06$) than the Grade 2 group ($M = 0.85$, $SE = 0.06$), $F(1, 195) = 159.73$, $p < .001$, $\eta\text{p}^2 = .45$. Bonferonni-adjusted follow-up analyses on the main effect of reader group, $F(2, 195) = 8.51$, $p < .001$, $\eta\text{p}^2 = .08$, confirmed that the below-average-readers ($M = 1.13$, $SE = 0.08$) scored significantly lower than the average-readers ($M = 1.42$, $SE = 0.07$), $t(120) = 3.34$, $p = .003$ and the above-average-readers ($M = 1.53$, $SE = 0.06$), $t(133) = 4.55$, $p < .001$, but that the average- and above-average-readers did not differ from one another, $t(143) = 1.13$, $p = .777$. Significant interactions emerged for Speed x Distance, $F(1, 195) = 51.67$, $p < .001$, $\eta\text{p}^2 = .21$, Grade x Distance, $F(1, 195) = 5.52$, $p = .02$, $\eta\text{p}^2 = .03$, Grade x Speed, $F(1, 195) = 11.09$, $p = .001$, $\eta\text{p}^2 = .05$, Grade x Distance x Speed, $F(1, 195) = 10.17$, $p = .002$, $\eta\text{p}^2 = .05$, and Grade x Reader Group x Speed, *F*(2, 195) = 4.00, *p* = .02, ηp² = .04. Follow-up analyses on the three-way interactions are discussed below as relevant to specific hypotheses.

Reading ability and AR efficiency (Hypotheses 5 and 6). Although the two-way Reader Group x Speed interaction for Hypothesis 5 was not significant (below-average-readers were expected to show a larger difference between the slow and fast speed conditions in comparison to better-able-readers), nor was the two-way Grade x Reader Group interaction significant for Hypothesis 6 (the difference between below-average-readers and better-able readers was expected to increase from Grade 2 to Grade 6), both of these interactions were qualified by the significant three-way interaction for Grade x Reader Group x Speed. The pattern of group mean scores for this interaction is plotted in Figure 4.

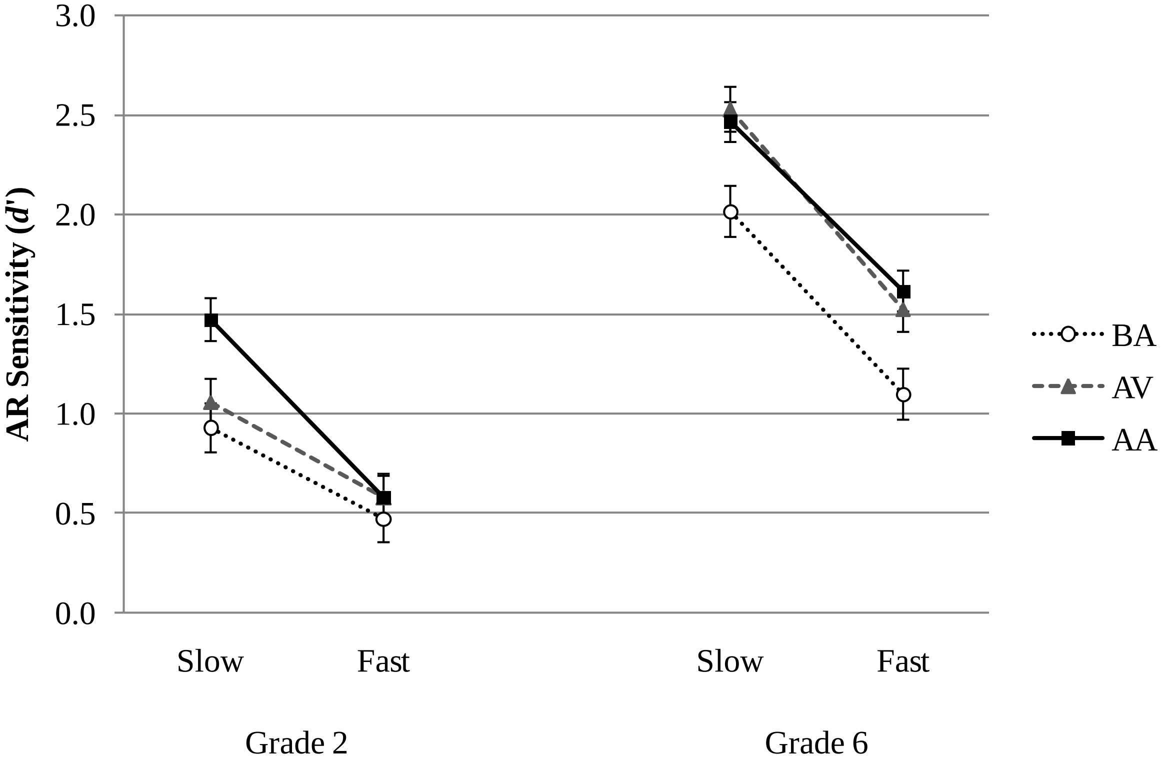

Figure 4. Mean AR sensitivity (*d*') in slow and fast speed trials for below-average (BA), average (AV) and above-average (AA) reader groups in Grade 2 (left) and Grade 6 (right). Error bars represent ± 1 standard error of the mean.

AR efficiency hypothesis (Hypothesis 5). Follow-up analyses for Hypothesis 5 looked to see if the effect of speed (difference in performance between the slow and fast speed conditions) differed among the reader groups separately at each grade (as would be indicated in Figure 4 by differences among the slopes of the reader group lines within each grade). The magnitude of the effect of speed was represented by a difference score (speed-dif), calculated for each participant by subtracting the marginal mean for the fast speed condition (AR-d-fast; averaged across distance conditions) from the marginal mean for the slow speed condition (AR-d-slow; averaged across distance conditions). Positive speed-dif scores represent relatively better performance in the slow speed condition compared to the fast speed condition. One-way ANOVA results on speed-dif scores by reader group were significant in Grade 2, $F(2, 94) = 3.71$, $p = .028$, but not in Grade 6, $F(2, 101) = 0.71$, $p = .493$. To follow up on the significant effect in Grade 2, the above-average-reader group was selected for a planned comparison with the below-average-reader group, based on the pattern of means for the Grade 2 reader groups depicted in Figure 4. This comparison showed that speed-dif scores were significantly larger (i.e., the slope was steeper) in the above-average-readers ($M = 0.81$, $SD = 0.67$) than the below-average-readers ($M = 0.45$, $SD = 0.81$), $t(64) = -2.64$, $p = .019$, which is contrary to the prediction that the below-average-readers would “catch up” to the other reader groups in the slow speed condition. Instead, the above-average-readers in Grade 2 showed a developmental advantage over the other reader groups in the slow speed condition. In Grade 6, all reader groups benefitted to the same degree from the reduced AR efficiency demands in the slow speed condition in comparison to the fast speed condition.

Reading-exposure hypothesis (Hypothesis 6). Follow-up analyses for Hypothesis 6 included two separate factorial ANOVAs, one at each level of speed, with grade and reader group as between-subjects factors. Marginal means at each level of speed (AR-d-slow and AR-d-fast; averaged across distance conditions) were used as the dependent variables. Above-average-readers were excluded from these analyses due to their developmental advantage in the slow speed condition in Grade 2. Independent sample *t*-tests confirmed that the average- and above-average-readers did not differ in performance in any of the other conditions, including the fast speed condition in Grade 2, $t(66) = -0.02$, $p = .986$, the slow speed condition in Grade 6, $t(75) = 0.70$, $p = .489$, and fast speed condition in Grade 6, $t(75) = -0.60$, $p = .553$. The average-readers were therefore equivalent to the above-average-readers in all conditions except for the slow speed condition in Grade 2, where the typical performance of average-readers provided a better test of Hypothesis 6 than would the superior performance of the above-average-readers. The interaction between grade and reader group in each ANOVA was examined to determine if the difference between the below-average-reader group and the average-reader group was larger in Grade 6 than in Grade 2. In both speed conditions, the patterns of means trended in expected directions, with a larger difference between the reader groups in Grade 6 than in Grade 2; however, neither Grade x Reader group interaction reached statistical significance; AR-d-slow: $F(1, 118) = 2.281$, $p = .134$, $\eta\text{p}^2 = .02$; AR-d-fast, $F(1, 118) = 1.91$, $p = .170$, $\eta\text{p}^2 = .02$. These results did not support the hypothesis of larger reader group differences in older children than in younger children.

Reading-age-match control group comparison (Hypothesis 6). The other test of the reading-exposure hypothesis involved a comparison of the reading-age-matched groups including the Grade 2 above-average-readers and the Grade 6 below-average-readers (see "Reader group assignment" above for a description of these groups). These groups were first compared on the dichotomized reading exposure variable using the non-parametric Mann-

Whitney *U* test. This test confirmed that the Grade 6 below-average-readers (mean rank = 26.30) were ranked lower than the Grade 2 above-average-readers (mean rank = 37.03), *U* = 332.0, *z* = -2.64, *p* = .008, indicating less average time spent reading for pleasure in the Grade 6 below-average-readers. This result is consistent with the assumption that these groups should have similar cumulative lifetime exposure to reading, based on their similar levels of reading achievement (assuming that the group differences in current reading exposure reflect a consistent pattern over the children's relative years of reading, with the older below-average-readers obtaining less reading exposure per year over a greater number of years and the younger above-average-readers obtaining more reading exposure per year over a fewer number of years).

Reading-age-matched groups were then compared on a measure of overall AR sensitivity, reflecting performance across all conditions. The index of overall AR sensitivity used here and in subsequent analyses (e.g., see "Influence of Sample Characteristics" and "Correlations" below) was a *d'* score calculated in the same manner as described above, under "Assessment of response bias", except that the original AR accuracy scores (proportion correct) for blue trials (hits) and orange trials (false alarms) were first averaged across all four Distance x Speed conditions. The overall AR sensitivity measure met the assumptions for parametric analyses. An independent sample *t*-test compared the reading-age-matched groups on overall AR sensitivity, finding better performance in the Grade 6 below-average-readers (*M* = 1.73, *SD* = 0.93) than the Grade 2 above-average-readers (*M* = 1.039, *SD* = 0.705), *t*(62) = -3.41, *p* = .001, ηp^2 = .16. This result suggests that chronological age was a stronger predictor of AR sensitivity than was exposure to reading in these groups.

General AR efficiency development (Hypothesis 7). Developmental changes in AR precision and AR efficiency that were independent of reading ability were evident from significant interactions between Grade x Distance and Grade x Speed, which were qualified by a significant three-way interaction of moderate effect size for Grade x Distance x Speed (this interaction also qualified the two-way Distance x Speed interaction). The pattern of group mean scores for this interaction is plotted in Figure 5.

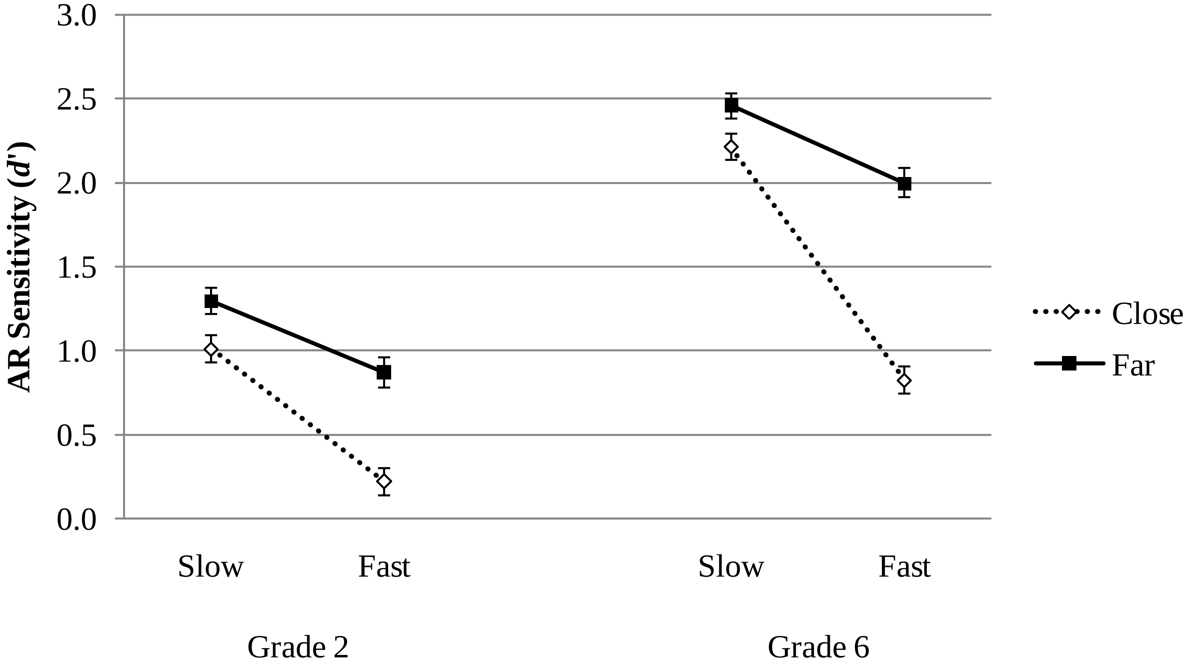

Figure 5. Mean AR sensitivity (*d*') in slow and fast speed trials for close and far distances in Grade 2 (left) and Grade 6 (right). Error bars represent ± 1 standard error of the mean.

Follow-up analyses in Grade 2 tested the prediction that Grade 2 children would perform poorly in the close distance condition regardless of dot-speed, but show a large effect of speed in the far distance condition. Paired sample *t*-tests compared the slow and fast speed conditions at each distance, where a significant effect was expected in the far distance condition only. Results showed that performance was better in the slow speed condition than the fast speed condition in both distance conditions; close distance: $t(96) = 7.81$, $p < .001$; far distance: $t(96) = 4.55$, $p < .001$. The relative magnitude of these effects was assessed by comparing two difference scores (close-dif, far-dif) that were calculated by subtracting performance in the fast speed condition from the slow speed condition within each distance. Contrary to predictions, a paired-sample *t*-test on the difference scores in Grade 2 showed that the effect of speed (magnitude of difference score) was larger in the close distance condition (close-dif: *M* = 0.80, *SD* = 1.01) than the far distance condition (far-dif: *M* = 0.46, *SD* = 0.99), *t*(96) = 2.67, *p* = .009. This result suggests that AR efficiency had a larger effect in the distance condition where AR precision demands exceeded – rather than met – the developmental threshold for Grade 2 children. The prediction that Grade 2 participants would replicate the results of Wolf and Pfeiffer (2014; i.e., obtain 75% accuracy in the far distance condition) in the far-slow condition only was assessed via visual inspection of mean AR accuracy scores (proportion correct; uncorrected for response bias). Mean Grade 2 AR accuracy was 73.49% in the far-slow condition, thus closely matching Wolf and Pfeiffer’s 75% accuracy threshold. This result increases confidence that differences in performance based on dot-speed are the result of changes in AR efficiency demands at an otherwise comparable baseline level of AR precision. Finally, it was predicted that Grade 2 children would perform similarly in the far-fast condition and the close distance condition(s). Given that differences were found between slow and fast speeds in the close distance condition, the far-fast condition was compared to the close-slow and close-fast conditions individually. Paired-sample *t*-tests revealed better AR sensitivity in the far-fast condition (*M* = 0.87, *SD* = 0.91) than the close-fast condition (*M* = 0.23, *SD* = 0.67), *t*(96) = 5.73, *p* < .005, but no difference between the far-fast condition and the close-slow condition (*M* = 1.03, *SD* = 0.96), *t*(96) = -1.49, *p* = .140. The latter result suggests that in the far-fast condition, low AR precision demands compensated for high AR efficiency demands to a similar degree that low AR efficiency demands compensated for high AR precision demands in the close-slow condition. On the other hand, the combination of high demands on both AR precision and efficiency in the close-fast condition exceeded the difficulty associated with high AR efficiency demands alone in the far-fast condition, suggesting an additive effect of AR precision and AR efficiency on performance.

Follow-up analyses in Grade 6 tested the prediction that performance would be better in the far distance condition and worse in the close distance condition regardless of speed, although a relatively higher score was predicted for the close-slow condition than the close-fast condition. A paired-sample t-test on the marginal means for distance (averaged across speed conditions) in Grade 6 confirmed higher AR sensitivity in the far distance condition than the close distance condition, $t(103) = -11.59$, $p < .001$. Within each distance, performance was also higher in the slow speed condition than the fast speed condition, close distance: $t(103) = -16.06$, $p < .001$; far distance: $t(103) = 5.77$, $p < .001$. The relative magnitude of the effect of speed within distance was larger in the close distance condition (close-dif: $M = 1.39$, $SD = 0.88$) than the far distance condition (far-dif: $M = 0.45$, $SD = 0.80$), : $t(103) = 7.71$, $p < .001$, which confirmed that the AR sensitivity of Grade 6 children at near-adult levels of AR precision depended heavily on AR efficiency demands. In fact, mean AR accuracy in the close-slow condition in Grade 6 was 90.38%, which exceeds the 75% accuracy threshold from Wolf and Pfeiffer (2014). Overall, the pattern of results in Grade 6 matched the pattern found in Grade 2, which suggests that AR efficiency demands (dot-speed) have the greatest impact on AR modulation performance when AR precision demands are high (and vice versa) across multiple stages of AR development.

Given the similar patterns of performance across conditions within Grades 2 and 6, the source of the significant Grade x Distance x Speed interaction was explored in terms of relative age-related improvements between the Grade 2 and Grade 6 groups. Visual inspection of Figure 5 suggested that the Grade 6 children differed from the Grade 2 children primarily in terms of the magnitude of the distance effect in the fast speed condition. Difference scores (slow-dif, fast-dif) were therefore calculated by subtracting the close distance from the far distance within each speed. Independent sample *t*-tests confirmed that the difference scores were significantly larger in Grade 6 than in Grade 2 in the fast speed condition, *t*(199) = -3.53, *p* = .001, but not in the slow speed condition, *t*(199) = 0.49, *p* = .628, indicating that the increase in AR precision demands from the far distance condition to the close distance condition reduced performance to a similar magnitude for children in Grades 2 and 6 when efficiency demands were low; however, this same increase in AR precision demands had a much larger effect in Grade 6 compared to Grade 2 when efficiency demands were high. The latter result appears to reflect a smaller improvement from Grade 2 to Grade 6 in the close-fast condition in comparison to age-related improvements in the other three conditions.

Influence of Sample Characteristics

Visual acuity. Eleven participants obtained “low” visual acuity scores (i.e., Snellen fraction denominator above 20; the maximum denominator was 33), nine of whom were in Grade 2. Overall AR sensitivity across all conditions (see “Reading-age-match control group comparison” above for a description of this measure) was compared between these nine Grade 2 participants and the remaining Grade 2 participants. The non-parametric Mann-Whitney *U* test was used for this comparison due to the unequal sample sizes between visual acuity groups. There was a trend for the “low” visual acuity group to rank lower on overall AR sensitivity compared to the “normal” visual acuity group in Grade 2, although this comparison did not reach statistical significance, *U* = 251.0, *z* = -1.80, *p* = .071. In Grade 6, only two participants fell in the “low” visual acuity group, both of whom were below-average-readers. Compared to the remaining Grade 6 below-average-readers, the mean ranks of the two “low” visual acuity participants were lower than the mean ranks of the remaining Grade 6 below-average-readers, $U = 0.0$, $z = -2.42$, $p = .016$, although this result is interpreted with caution given the small sample size in the Grade 6 “low” visual acuity group. Nevertheless, in order to rule out the potential effect of visual acuity on the results, the primary 2 x 3 x 2 x 2 ANOVA with mixed factors grade, reader group, distance, and speed was re-run, excluding participants from the “low” visual acuity group across grades. All main effects and interactions remained significant and of similar effect size magnitude. Visual acuity is therefore unlikely to account for the observed effects.

Demographic variables. The impact of demographic factors on the primary results was examined for those variables identified in “Sample Characteristics” above as differing between groups. The variables found to differ among the reader groups included age (in months), income, and parental education, and between grades included home language (i.e., whether English was spoken in the home). The influence of these variables on the AR task results are first discussed for the continuous variable, age, followed by the three dichotomous variables.

Age. Reader group differences in age were assessed for their implications on the interpretation of reader group effects. The age differences in Grade 2 were not of concern since the Grade 2 below-average-readers were older than the average-readers (mean group difference: 2.63 months) and the above-average-readers (mean group difference: 3.71 months). Reader group effects in Grade 2 showing poorer AR sensitivity in the below-average-readers were therefore found in spite of this group’s slight age-based advantage. In contrast, Grade 6 above-average-readers were, on average, 2.48 months older than the below-average-readers, giving them a slight age-based advantage in addition to higher reading scores. A regression analysis of Grade 6 data only was performed to disentangle the unique contributions of age and reading achievement on overall AR sensitivity scores across conditions (see “Reading-age-match control group comparison” above for a description of this measure). The variables in the model included age (in months) and reading efficiency composite scores. The model was significant, $F(2, 101) = 8.11$, $p = .001$, and accounted for 12.1% of the variance overall AR sensitivity in Grade 6 (adjusted $R^2 = .12$). Importantly, after controlling for the strong unique effect of reading efficiency on overall AR sensitivity scores ($p < .001$), age did not account for additional unique variance ($p = .452$). Therefore, results showing better AR sensitivity in Grade 6 above-average-readers compared to Grade 6 below-average-readers are best attributed to these participants’ superior reading ability rather than their age-based advantage, which was very minor.

Dichotomous variables. The three dichotomous variables (income, parental education, home language) were individually entered with distance and speed into a 2 x 2 x 2 mixed factorial ANOVA to assess for systematic differences in overall performance based on demographic variables (main effects) and for unique influences of demographic variables on performance for specific distance or speed conditions (interactions).Variables found to influence AR task performance were then assessed on the degree to which their influence was independent of or shared with the group factor of interest on which they differed (i.e., grade or reader group). Shared associations with reading ability were of particular interest given that demographic characteristics such as income and parental education are associated with factors that influence children’s reading development, including the quantity and quality of language exposure and reading opportunities in the home. Shared associations of demographic variables with AR task performance and reading ability would shed light on underlying factors that may contribute to struggling readers’ delayed AR modulation development.

The only significant result from the ANOVA analyses was a main effect of small effect size for parental education. Participants whose parents completed post-secondary education had better AR-d scores (*M* = 1.50, *SE* = .07) than those whose parents did not complete post-secondary education (*M* = 1.18, *SE* = .102), *F*(1, 189) = 6.63, p = .011, ηp² = .034. The main effects for income, *F*(1, 185) = 3.08, *p* = .081, ηp² = .016, and home language, *F*(1, 189) = 3.11, *p* = .079,ηp² = .016, did not reach significance. Children from low income homes (*M* = 1.32, *SE* = .08) had marginally lower scores than children from high income homes (*M* = 1.52, *SE* = .09), and children from non-English homes (*n* = 33; *M* = 1.62, *SE* = .13) had marginally higher scores children from English-speaking homes (*n* = 156; *M* = 1.36, *SE* = .06). There were no significant interactions between any demographic variable and distance or speed.

To test for a shared association of parental education with reading ability, groups of high and low parental education were compared on reading efficiency. This comparison was completed using the non-parametric Mann-Whitney *U* test due to the unequal sample sizes between parental education groups. The result confirmed that children from the high parental education group were ranked as better readers, on average, than children from the low parental education group, *U* = 5205.0, *z* = 3.715, *p* < .001. Hierarchical multiple regression was therefore conducted to determine if the addition of parental education improved the prediction of overall AR sensitivity scores over and above grade and reading efficiency. Standardized regression coefficients are presented in Table 7 under “Model 2” (Models 3 and 4 are discussed below under “Parental education and children’s intelligence”). The full model of grade, reading efficiency, and parental education (Model 2) was statistically significant, R^2 = .50, *F*(3, 186) = 61.73, *p* < .001; adjusted R^2 = .49. The addition of parental education led to a significant increase in R^2 of .01, *F*(1, 186) = 4.39 , *p* = .037. All three variables in Model 2 accounted for unique variability in AR sensitivity. Importantly, the significant effect of reading efficiency after controlling for parental education indicates that reader group differences on the parental education variable do not fully account for the observed reader group effects on AR task performance in the primary results.

Table 7

Standardized Regression Coefficients for Predictors of Overall AR Sensitivity

	Model 2		Model 3		Model 4	
Parameter	β	p	β	p	β	p
Grade	.649	< .001	.660	< .001	.666	< .001
Reading efficiency	.170	.002	.066	.316	-.033	.656
Parental education	.112	.037	.081	.134	.093	.082
Verbal IQ	--	--	.174	.008	.145	.027
Nonverbal IQ	--	--	.026	.656	-.009	.877
Phonological proc.	--	--	--	--	.193	.007
Rapid naming	--	--	--	--	.01	.855

Exploratory Analyses on Predictors of Attention Resolution Sensitivity

Correlations. Correlation analyses were conducted to explore the associations between hypothesized predictors of AR sensitivity and overall AR sensitivity scores. Pearson correlations were computed for the continuous predictor variables including age (in months) and all of the reading-related measures and IQ measures. Correlations with the non-continuous variables reading exposure and gaming exposure were completed using Spearman's rho (r_s), a robust non-parametric alternative to Pearson correlation (r_p) that tests for an association between the rank orderings of paired data points on two continuous or ordinal variables (Laerd Statistics, 2018b). Spearman's rho ranges from 0 (no association) to 1 (perfect association) and is typically interpreted in a similar manner as Pearson correlation, albeit somewhat more cautiously for borderline cases (Howell, 2013). Due to violations of statistical assumptions in many of the continuous independent measures (see "Assessment of Parametric Statistical Assumptions" above), Pearson correlations were also verified using Spearman's rho, although the Spearman results are only discussed in the text when discrepant from the Pearson analyses. Analyses were conducted at each grade level in order to capture developmental changes in the pattern of associations (see Table 8 for the Grade 2 correlations and Table 9 for the Grade 6 correlations).

The results in Grade 2 revealed significant positive correlations with overall AR sensitivity and reading efficiency (composite score), Phoneme Decoding Efficiency, phonological processing, and verbal IQ. The fact that associations were found with both Phoneme Decoding Efficiency and phonological processing suggests a potential link between AR modulation abilities and phonological processes, given that phonological processes are integral to decoding abilities (as measured with Phoneme Decoding Efficiency). The correlation with reading efficiency was not significant based on Spearman's rho and should therefore be interpreted with caution, although the reading efficiency composite met the assumptions for parametric analyses in Grade 2. Interestingly, no association was found between overall AR sensitivity and the Sight Word Efficiency subtest, which is the principal index of reading achievement on the TOWRE-2. This pattern of results suggests that the association between AR sensitivity and the reading efficiency composite was driven primarily by the Phoneme Decoding Efficiency subtest. All associations were small in magnitude, ranging from $r_p = .20$ for Phoneme Decoding Efficiency to $r_p = .29$ for phonological processing.

The results in Grade 6 revealed significant positive associations between overall AR sensitivity and reading efficiency (composite and subtest scores), phonological processing, verbal IQ, and nonverbal IQ. All associations were small in magnitude, ranging from $r_p = .30$ for phonological processing.

Parental education and children's intelligence. In light of the significant positive correlations found between the IQ measures and overall AR sensitivity, and with theoretical

Table 8

Correlations for Grade 2 Participants

	Overall AR-d[a] 1	Age[b] 2	Reading efficiency[c] 3	Sight Word Efficiency[d] 4	Phoneme decoding[d] 5	Phonological processing[e] 6	Rapid naming[f] 7	Verbal IQ[g] 8	Nonverbal IQ[h] 9	Reading exposure[i] 10	Gaming exposure[i] 11
1		.17	.21*	.11	.20*	.29**	.16	.27**	.03	.18	-.06
2			-.41**	-.44**	-.33**	-.37**	-.20*	-.20*	-.37**	-.01	-.17
3				.84**	.97**	.74**	.46**	.59**	.54**	.10	.22*
4					.75**	.58**	.34**	.60**	.53**	.14	.18
5						.74**	.43**	.54**	.49**	.07	.19
6							.30**	.45**	.46**	.05	.12
7								.40**	.24*	.18	.23*
8									.41**	.21*	.23*
9										.06	.24*
10											.16

Note. Pearson correlations (r_p) are provided for continuous variables, numbered 1 – 9. Spearman correlations (r_s) are provided for non-continuous variables, numbered 10 and 11.

[a]AR sensitivity (*d*') across distance and speed conditions. [b]Unit of measurement is in months. [c]TOWRE-2: composite standard score. [d]TOWRE-2: subtest standard score. [e]CTOPP-2: Elision subtest scaled score. [f]CTOPP-2: composite standard score. [g]PPVT-4: standard score. [h]WASI-II: Matrix Reasoning subtest, *T*-score. Missing data for one below-average-reader. [i]Dichotomous variables were created based on a within-grade median-split of the ranked raw scores on socio-demographic questionnaire items for time spent reading for pleasure and time spent playing action video games. Raw scores were measured in units of minutes per week.

$*p < .05$, $**p < .01$

Table 9

Correlations for Grade 6 Participants

	Overall AR-d[a] 1	Age[b] 2	Reading efficiency[c] 3	Sight Word Efficiency[d] 4	Phoneme decoding[d] 5	Phonological processing[e] 6	Rapid naming[f] 7	Verbal IQ[g] 8	Nonverbal IQ[h] 9	Reading exposure[i] 10	Gaming exposure[i] 11
1		.17	.37**	.30**	.37**	.39**	.14	.38**	.34**	.11	.16
2			.27**	.31**	.24*	.31**	.03	.13	.34**	.20*	.05
3				.87**	.96**	.57**	.49**	.57**	.39**	.23*	.10
4					.74**	.54**	.39**	.49**	.39**	.24*	.11
5						.54**	.48**	.52**	.35**	.24*	.07
6							.21*	.53**	.47**	.01	.18
7								.24*	.10	.17	.05
8									.43**	.01	.21*
9										.06	.02
10											-.02

Note. Pearson correlations (r_p) are provided for continuous variables, numbered 1 – 9. Spearman correlations (r_s) are provided for non-continuous variables, numbered 10 and 11.

[a] AR sensitivity (*d*') across distance and speed conditions. [b] Unit of measurement is in months. [c] TOWRE-2: composite standard score. [d] TOWRE-2: subtest standard score. [e] CTOPP-2: Elision subtest scaled score. [f] CTOPP-2: composite standard score. [g] PPVT-4: standard score. [h] WASI-II: Matrix Reasoning subtest, *T*-score. [i] Dichotomous variables were created based on a within-grade median-split of the ranked raw scores on socio-demographic questionnaire items for time spent reading for pleasure and time spent playing action video games. Raw scores were measured in units of minutes per week.

*$p < .05$, **$p < .01$

reason to believe that parental education influences children's intellectual development, Model 2 of the prior multiple regression analysis was revisited in order to explore whether IQ might account for the unique effect of parental education on AR sensitivity, controlling for reading ability. The Mann-Whitney *U* test confirmed that children from the high parental education group were ranked higher, on average, than those from the low parental education group on verbal IQ, $U = 5380.50$, $z = 4.21$, $p < .001$, and nonverbal IQ, $U = 4604.50$, $z = 2.23$, $p = .026$. Verbal IQ and nonverbal IQ scores were therefore added to grade, reading efficiency, and parental education in a third regression model, and this led to another significant increase in R^2 of .02, $F(2, 186) = 4.10$, $p = .018$. The effect of verbal IQ was significant whereas the effect of nonverbal IQ was not significant (see Model 3 in Table 7 for the standardized regression coefficients). Importantly, parental education and reading efficiency were no longer significant after adding the IQ measures in Model 3. These results suggest that (a) AR task performance is related to verbal IQ but not nonverbal IQ, and (b) verbal IQ is a stronger predictor of AR sensitivity than is parental education. The non-significant effect of reading efficiency after controlling for verbal IQ is consistent with the known relationship between verbal skills and reading ability (Kudo et al., 2015) and the higher verbal IQ scores in the above-average-readers in the current sample.

Reading processes. The fourth and final regression model added rapid naming and phonological processing scores to explore the influence of specific reading-related processes on the previously identified effects on AR sensitivity (see Model 4 in Table 7 for the standardized regression coefficients). The full model of grade, reading efficiency, parental education, verbal IQ, nonverbal IQ, phonological processing, and rapid naming was statistically significant, $R^2 = .54$, $F(7, 182) = 30.42$, $p < .001$; adjusted $R^2 = .52$. The addition of phonological processing and rapid naming scores led to a significant increase in R^2 of .02, $F(2, 182) = 3.74$, $p = .026$. The effect of phonological processing was significant whereas the effect of rapid naming was not significant. There were no changes in the pattern of statistically significant results among the other variables. That is, significant unique effects were observed for grade, verbal IQ, and phonological processing, while the effects of reading efficiency, parental education, nonverbal IQ, and rapid naming were non-significant. Thus, even after controlling for significant factors such as grade and verbal IQ, specific reading-related processes continued to account for individual differences in AR modulation skills. Contrary to the expectation that AR abilities would be more strongly related to measures associated with reading fluency such as rapid naming (Norton & Wolf, 2012), AR modulation was more strongly related to a measure of phonological processing. Possible explanations for these results are presented in the Discussion.

Exploratory Analyses on Predictors of Reading Achievement

The degree to which AR sensitivity predicted reading achievement in relation to other reading-related factors was explored using hierarchical multiple regression. Raw Sight Word Efficiency subtest scores were used as the dependent measure so that both reading achievement and AR sensitivity could vary with age, given that the AR Sensitivity scores are not age-normative. After controlling for age (in months; Model 1), overall AR sensitivity accounted for significant additional variance (Model 2), R^2 change = .04, $F(1, 198) = 17.63$, $p < .001$. Model 3 added reading exposure and gaming exposure, of which only reading exposure had a unique effect. Subsequent models added each of the following variables individually: rapid naming (Model 4), phonological processing (Model 5), and verbal IQ (Model 6). All models were statistically significant. The pattern of variables with significant effects remained the same across models except for AR sensitivity which was significant in Models 3 and 4 but not in Models 5 or

6. Standardized regression coefficients for Models 2, 4 and 6 are presented in Table 10 to show the highest model in which AR sensitivity remained significant (Model 4) in comparison to its baseline model (Model 2) and the model including all factors (Model 6).

Table 10

Standardized Regression Coefficients for Predictors of Reading Achievement

	Model 2		Model 4		Model 6	
Parameter	*β*	*p*	*β*	*p*	*β*	*p*
Age (in months)	.507	< .001	.596	< .001	.717	< .001
AR sensitivity	.280	< .001	.213	.001	.008	.884
Gaming exposure	--	--	.036	.434	-.036	.337
Reading exposure	--	--	.094	.042	.095	.012
Rapid naming	--	--	.238	< .001	.145	< .001
Phonological proc.	--	--	--	--	.311	< .001
Verbal IQ	--	--	--	--	.179	< .001

Discussion

This study examined the efficiency of attention resolution (AR) modulation in children in Grades 2 and 6 at three levels of reading ability (below-average, average, and above-average). AR modulation refers to the ability to flexibly and efficiently adjust the grain of visuo-attentional focus to the appropriate size in order isolate (i.e., individuate) an item from neighbouring items in a cluttered visual display. AR modulation has intuitive relevance to reading and learning to read given that letters must be individuated from other closely-spaced letters in order to decode words. The primary purpose of the current study was to explore the link between AR modulation efficiency and reading ability. A focus on AR efficiency was motivated by slower perceptual processing speeds observed in children with reading difficulties (e.g., Stenneken et al., 2011), as well as reading fluency deficits that often remain after phonological-based reading interventions (thus pointing to a non-phonological efficiency-based deficit; Wolf et al., 2002). As a secondary goal, the current study aimed to extend previous research on AR modulation precision in typically developing children (Wolf & Pfeiffer, 2014) to see if AR development is tied to efficiency in resolving attention. Wolf and Pfeiffer measured AR precision using a dot-tracking task by varying the minimum distance between the target dot and distractor dots on dot-passes during visual tracking. The current study adapted this task to compare two levels of AR efficiency (slow and fast dot-movement speeds) at two levels of AR precision (close and far minimum dot-pass distances). Differences in dot-tracking accuracy (converted to a *d*' AR sensitivity score) based on distance, speed, grade, and reader group are discussed below as relevant to the goals of the study. General results pertaining to the role of efficiency in AR modulation (the secondary goal) are described first in order to provide a background for the discussion of the primary results relating AR efficiency to reading ability.

General AR Modulation Efficiency

In order to explore the interdependence of AR precision and AR efficiency at different stages of development, the chosen dot-pass distances for the dot-tracking task either met or exceeded the distance thresholds identified by Wolf & Pfeiffer (2014) for the age groups in this study. By comparing slow and fast speed conditions at previously established distance thresholds, this study explored (a) whether Grade 2 children remain successful in tracking the dot at a comfortable dot-pass distance (far distance) when AR efficiency demands are high (fast speed), and (b) whether Grade 6 children can reach adult levels of AR precision (close distance) when AR efficiency demands are low (slow speed). This is the first study to examine both AR precision and AR efficiency. Hypotheses about the patterns of performance across conditions were therefore exploratory in nature. It was predicted that Grade 2 children would have difficulty in the close distance condition regardless of dot-speed due to the high AR precision demands in this condition, but that an effect of AR efficiency would be most prominent in the age-appropriate far distance condition. As expected, Grade 2 children performed better in the far distance condition than the close distance condition. Contrary to predictions, the effect of AR efficiency was significantly larger in the close distance condition compared to the far distance condition. The same pattern of results was found in Grade 6 as in Grade 2, but at a higher overall level of performance across conditions. The degree of improvement from Grade 2 to Grade 6 was similar across conditions except for the most difficult close-fast condition where there was less improvement from Grade 2 to Grade 6. Overall, the results indicate that precision and efficiency demands have additive effects on AR performance across the stages of development in Grades 2 and 6. The large improvement of Grade 2 children from the fast speed to the slow speed condition at the close distance further suggests that children as young as Grade 2 can reach adult levels of AR precision to some degree (albeit at a lower level of accuracy compared to Grade 6 children and compared to Wolf and Pfeiffer’s 75% accuracy threshold), but that their degree of success depends largely on AR efficiency demands. Results emphasize that AR efficiency is an important component of children’s AR modulation ability.

AR Efficiency Hypothesis

It was primarily hypothesized that below-average-readers would show less skill in AR modulation in comparison to average- and above-average-readers, but that that the differences among the reader groups would diminish under conditions of low AR efficiency demands (slow speed condition). The results supported the first component of this hypothesis in that below-average-readers performed more-poorly overall compared to average- and above-average-readers. The second component of this hypothesis was not supported in that the performance of below-average readers did not “catch up” to the other reader groups when AR efficiency demands were low compared to when AR efficiency demands were high (slow vs. fast speed condition). Instead, the above-average-readers in Grade 2 demonstrated an advantage over the other Grade 2 reader groups in the slow speed condition but not the fast speed condition. This ‘good-reader-advantage’ in Grade 2 was maintained and extended to the average-readers in Grade 6, where the performance of the average- and above-average-reader groups was identical and equally superior to the performance of below-average-readers in both speed conditions.

That a unique benefit for above-average-readers was observed only in Grade 2 in the slow speed condition might suggest that efficient AR modulation skills offer a potential advantage in the early- to intermediate-stages of learning to read (although see below for alternate explanations for these results). It is possible that superior AR efficiency in the Grade 2 above-average-readers enabled them to benefit more than the less-able readers in Grade 2 from the increased processing time provided in the slow speed condition (whereas the efficiency demands in the fast speed condition may have been too severe for even the above-average-readers at this stage of development). Grade 2 is an early stage in AR development (Wolf & Pfeiffer, 2014) but an intermediate stage in learning to read when reading materials include increasingly longer words and passages of text that place greater demands on AR modulation skills. The development of more-efficient AR skills earlier in life may better equip children to meet increasing AR demands during early reading instruction, thus giving them an advantage in overall reading development. For instance, efficient isolation of letters within words could free up cognitive resources and facilitate other processes involved in learning to read such as mapping phonemes to appropriate letters. This interpretation coincides well with the association found between AR sensitivity and phonological processing in the current study.

An alternate explanation of the Grade 2 ‘good-reader-advantage’ is that higher levels of reading exposure in good readers might facilitate AR development (instead of good AR modulation facilitating reading development). The act of reading requires focused visual-spatial attention to letters and words over extended periods of time, thereby providing repeated opportunities to practice AR modulation skills. Previous research indicates that struggling readers do not read as often or as much as their typically-reading peers (van Bergen et al., 2018). If reading exposure plays a significant role in AR development, it follows that the Grade 2 above-average-reader advantage could result from greater reading exposure in this group. No differences in reading exposure were detected among the reader groups in Grade 2 to support this explanation; however, the role of reading exposure should not be ruled out since the reading exposure variable was based on retrospective estimates of children’s time spent reading, and the raw scores were further dichotomized due to the unreliability of retrospective reporting. The primary purpose of this convenience-based measure was to supplement analyses of the reading exposure hypotheses (discussed below under “Reading-Exposure Hypothesis”).

An additional consideration in interpreting the interaction involving grade, speed, and reader group is that the equally low performance among the Grade 2 reader groups in the fast speed condition could reflect a developmental limitation in AR efficiency for this age group. If the efficiency demands in the fast speed condition were too high for this age group as a whole, floor effects would prevent differences based on reader group (or any other factor) from emerging in this condition. A shared “floor” among Grade 2 children in the fast speed condition but not in the slow speed condition could present as an interaction of speed with reader group in Grade 2 where in fact only a main effect of reader group would normally exist, had all conditions been within their developmental range of AR efficiency. Note, however, that AR sensitivity in the fast speed condition was above-chance. Furthermore, differences between distance conditions were found in the fast speed condition in Grade 2 when averaged across reader groups (as discussed under “General AR Modulation Efficiency” above). These effects would not be expected if the fast speed condition exceeded a fundamental developmental limit in AR efficiency. Nevertheless, the interaction between reader group and speed in Grade 2 but not in Grade 6 should be interpreted with caution since the relative overall difficulty of the two distance conditions in this study was higher for children in Grade 2 than for children in Grade 6.

The most definitive conclusion that can be drawn from the interaction results is that the below-average-readers consistently performed more poorly than the other grade-matched reader groups in the conditions known – based on good performance in the typical readers and prior research (Wolf & Pfeiffer, 2014) – to be within their respective developmental ranges of AR precision and efficiency. This pattern of results points toward a general developmental delay in AR modulation in struggling readers rather than an effect of AR efficiency specifically.

Reading-Exposure Hypothesis

The primary test of the reading-exposure hypothesis involved comparing the magnitude of reader group difference on AR task performance in Grade 2 to the magnitude of reader group difference on AR task performance in Grade 6. The premise behind this analysis was that struggling readers lag progressively behind their peers in reading exposure over time (van Bergen et al., 2018). If reading exposure contributes significantly to the development of AR modulation, it follows that struggling readers will lag progressively behind their peers in AR modulation over time as well. The results of this analysis did not support the reading-exposure hypothesis in that the reader group differences in Grade 6 were not significantly larger than the reader group differences in Grade 2. Despite trends in the pattern of group means in the expected directions (showing larger reader group differences in Grade 6 than in Grade 2), the interaction effects between grade and reader group did not reach statistical significance. These non-significant results stood in contrast to supplementary analyses on parent-reported reading exposure in Grade 6, which showed that below-average-readers in Grade 6 spent less time reading for pleasure on average in comparison to average- and above-average-readers, who did not differ. In addition, a comparison between younger and older children who were matched on reading ability (Grade 2 above-average-readers and Grade 6 below-average-readers, respectively) found that the older children outperformed the younger children on AR task, despite having similar levels of reading achievement (and presumably similar levels of reading exposure). In conjunction, these results suggest that chronological age and reading ability were stronger drivers of AR modulation development in the current sample than was exposure to reading, at least across the widely different stages of development examined in this study.

The apparent lack of influence of reading exposure on AR modulation is inconsistent with the hypothesis that a developmental delay in AR modulation in struggling readers would be due to limited reading exposure. One reason for the lack of a reading exposure effect could be due to the unreliable nature of the reading exposure measure, which was based on retrospective reports. Another possibility, given the known developmental differences in AR modulation skills in the studied age groups (Wolf & Pfeiffer, 2014), is that the impact of reading exposure might become more apparent in groups that are closer in chronological age. Strong maturation effects on AR abilities can be reasonably expected given the variety of daily activities other than reading that recruit AR modulation (e.g., playing action video games). In order for reading exposure to have a measureable impact on AR performance over and above other age-related opportunities for AR development, the difference in reading exposure between good and poor readers would likely need to be quite large, and the difference in chronological age relatively small.

As for the hypothesized association between playing action video games and AR development, no associations were found in this study. Note, however, that gaming exposure was measured in the same manner as reading exposure using retrospective estimates of the current number of minutes spent playing action video games per week.

Exploration of Underlying Factors for Reader Group Differences

Exploratory analyses on reading-related predictors of overall AR performance suggested that general AR sensitivity was most strongly associated with phonological processing and verbal cognition. Both of these are viable underlying factors for reader group differences in AR modulation because they (1) differed among the current reader groups, (2) are theoretically relevant to reading ability, and (3) are consistent with prior research on reader group differences in cognition (Kudo et al., 2015). An indirect association was also found with the parental education variable (proportion of parents with a post-secondary degree), on which the reader groups also differed and which is related to children's reading development (parents with higher levels of education are more likely, on average, to provide language-rich home environments with ample reading-related resources); however, the association with parental education became non-significant after controlling for children's verbal cognition.

This pattern of results, although exploratory, was contrary to the prediction that AR modulation would be more strongly related to reading measures associated with reading fluency such as rapid naming. In fact, rapid naming showed no association with overall AR sensitivity despite accounting for significant variance in the reading efficiency scores that were used to define the reader groups. In contrast, phonological processing and verbal cognition each accounted for unique variance in both AR sensitivity and reading efficiency. Moreover, the influence of AR sensitivity became non-significant in accounting for variance in reading efficiency after controlling for phonological processing. Note, however, that phonological processing skills can also predict reading fluency since poor decoders with phonological processing deficits are by definition also dysfluent readers. More-nuanced causal links between phonology and reading fluency may also exist. For example, a recent study by Knoop-Van Campen, Segers, and Verhoeven (2018) found that phonological processing mediated the relationship between working memory and reading efficiency in fourth-grade children with dyslexia. In order to detect a unique role of AR modulation in predicting reading fluency, if this exists over and above phonological processing, it may be necessary to study children for whom phonological processing is no longer the primary factor contributing to reading fluency deficits, such as after children successfully complete a phonological intervention.

Another recent study that may shed light on the underlying nature of AR deficits in struggling readers is a follow-up study by Wolf and colleagues (2018) on the neural basis of AR precision development. AR performance was measured in 7- and 11-year-old children and adults across four dot-pass distance conditions using functional magnetic resonance imaging (fMRI). Analyses distinguished between brain regions activated by dot-tracking ability in general, and regions whose level of activation depended on AR precision demands across the different distance conditions. Included among the brain regions that were responsive to increases in AR precision demands were the fronto-insular cortex and anterior cingulate cortex. Together, these regions comprise the insular-cingulate neural network, one of three distinct functional networks of cognitive control that is also referred to as the *salience network* (Sridharan, Levitin, & Menon, 2008). The salience network is thought to identify personally relevant stimuli, and to direct – or switch between – modes of activation in the other two neural networks of cognitive control. Critically, the salience network is said to switch activation from the default-mode network (associated with internal processing) to the central executive network (associated with external processing) in order to recruit additional resources to process personally relevant and cognitively demanding tasks.

A link between AR modulation and the salience network could have important implications for understanding the role of AR modulation in reading difficulties. Twait, Farah and Horowitz-Kraus (2018) found decreased functional connectivity of the salience network in struggling readers. The authors highlighted a critical role of the salience network in executive cognitive functions such as error monitoring that are also abnormal in struggling readers (Horowitz-Kraus & Breznitz, 2008). Speculatively, if the AR modulation demands associated with letter isolation during reading depend on activation of the salience and/or central executive network, it might suggest that AR deficiencies in struggling readers are more closely related to executive function deficits in this population (e.g., Brosnan et al., 2012) than to basic visual processes. This interpretation might account for the consistently lower performance in the below-average-readers compared to same-age children across distance and speed conditions. That is, failure of the salience network to recruit the processing resources necessary to modulate AR would decrease performance regardless of the degree of modulation required. Further exploration of this interpretation could broaden the conceptualization of how previously identified ‘network switching deficits’ in dyslexia (e.g., error monitoring) might impair reading to also include letter isolation deficits, which in turn may link the salience network and/or executive functioning to other effects associated with reading disability such as letter position uncertainty (Collis et al., 2013; Whitney & Cornelissen, 2005), crowding (Callens et al., 2013; Martelli et al., 2009), and wider letter spacing requirements for optimal reading (Perea et al., 2012; Zorzi et al. 2012).

Limitations and Future Directions

This study took an important first step in demonstrating the importance of both AR precision and AR efficiency in the development of AR modulation skills among children. It would be beneficial for future research to evaluate the relative importance of each of these factors more thoroughly. Results showed that the effect of each factor increased or decreased depending on the demands of the other factor, where larger effects were found under more demanding conditions. Given that only two conditions each were tested of distance and speed, and that the conditions chosen were fairly extreme for the age groups studied, it was not possible to assess the relative importance of AR precision and AR efficiency across the spectrum of conditions that likely require AR modulation in daily life. Future research could extend the current findings to explore the degree to which changes in precision impact efficiency, and vice versa, by testing multiple levels of distance and speed between these extremes while holding the other factor constant and comparing the rates of change in performance.

It would also be beneficial in future research to explore whether the combined demands of AR precision and AR efficiency impact adults to a similar degree as older children. In the 2018 study by Wolf and colleagues, AR dot-tracking accuracy (proportion correct) in 11-year-old children and adults was compared in multiple dot-pass distances conditions (rather than identifying the one distance threshold per age group that corresponded to 75% accuracy). Similar proportion correct accuracy for 11-year-olds and adults in all except for the most difficult condition led the authors to infer that the majority of AR precision development seems to occur by 11 years of age. It would be interesting to see if larger differences between older children and adults might emerge at these same distances with additional AR efficiency demands.

In addition, it would be beneficial to develop alternate methods of measuring AR efficiency that do not involve motion processing, if possible. A motion-free task would be particularly relevant to future studies on struggling readers, for whom magnocellular visual processing deficits have been linked to decreased motion sensitivity in certain tasks (Stein, 2001). At the present time, AR-like tasks that do not involve motion tracking typically take the form of flanked object identification tasks. Such tasks recruit cognitive processes extraneous to visual-attention such as visual feature integration or semantic memory when labelling objects. Results from flanker studies are also interpreted as crowding effects, which is problematic since the debate among researchers on the role of AR modulation in crowding has yet to be resolved (Levi, 2008). In fact, even the current study cannot rule out the influence crowding effects on the results, if indeed crowding is ultimately deemed to be pre-attentive and independent of AR. The value in the AR dot-tracking task is that it better isolates visual-attentional processing than flanker tasks, with the caveat of motion processing demands. The current study ensured basic dot-tracking capabilities of participants involving motion perception through the inclusion of practice dot-tracking trials; however, a more-extensive measure of general tracking ability could be added in future studies to better control for motion-processing artefacts on the results.

The development of reliable methods for estimating AR modulation in children younger than 7 years of age would be also beneficial for the purpose of clarifying whether AR deficiencies in struggling readers represent a developmental delay or a pre-existing deficit. The current results point toward there being a developmental delay; however, stronger conclusions could be drawn by following pre-reading children with and without risk-factors for reading disability longitudinally until struggling readers could be reliably identified. If at-risk children who later become struggling readers have poorer AR modulation skills compared non-at-risk children both prior to and after the onset of reading instruction, it would support a pre-existing deficit in AR modulation. In this case, pre-reading AR skills could be measured to screen children for risk of developing later reading difficulties. Alternately, if at-risk children who later become struggling readers only show deficits compared to non-at-risk children after the onset of reading instruction, but not prior to reading instruction, it would confirm the current results indicating a developmental delay.

The role of limited reading exposure in delaying AR development in struggling readers could be further studied by comparing avid readers to poor readers who experience a measurable aversion to reading (e.g., perceived threat toward reading-related stimuli has been demonstrated in reluctant readers using a visual dot-probe task; Nielen, Mol, Sikkema-de Jong, & Bus, 2016). Ideally, longitudinal research could find a way of reliably tracking reading exposure over time, perhaps by asking participants to log the titles of books read from beginning to end of the study.

In regard to children’s distractibility during the AR task, future studies would do well to include eye tracking data to ensure results are based on trials with appropriate attention to the task. Trials with a correct response would be counted as “valid” if eye-gaze was never averted from the target dot; trials with an incorrect response would be considered “valid” if the timing of gaze aversion coincided with a target-distractor dot-pass. Temporally precise eye tracking data indicating the point at which the target-dot was “lost” on incorrect trials might further uncover a wider range of individual difference in AR modulation skill. For example, two children might obtain identical accuracy scores, yet differ on the number dot-passes per incorrect trial during which they remained successful in tracking the target dot before it was lost.

In the absence of an eye tracking device, other sources of measurement error could be reduced in future studies by asking children to indicate after each response whether or not it was a guess. Recording guesses would correct for measurement error on trials where a correct response was provided by chance, thus correcting for response bias in cases where a child systematically chose one target colour over the other when guessing. The current study's method of converting accuracy scores into *d*' sensitivity scores was appropriate for reducing the impact of response bias on the results (Stanislaw & Todorov, 1999); however, it is possible that recording guesses could further improve estimates of effect size in future studies. Recording guesses has proven effective in correcting for a similar but different form of response bias in psychophysical stimulus detection studies (García-Pérez & Alcalá-Quintana, 2010).

Conclusion

This study makes a valuable contribution to fields of research related to attentional development in typically developing children as well as children who struggle to learn to read. The results suggest that struggling readers do not experience a developmental deficit in AR modulation because they progressed more in AR than their reading abilities would indicate. Neither was there evidence for a specific deficiency based on AR efficiency since the sensitivity differences between below-average- and average readers were equal across speed conditions. Stronger evidence was provided for a general developmental delay in AR modulation, since below-average readers consistently performed worse than better-able readers in their own age-group, but better than younger reading-age-matched children. Future research is needed to explore the role of reading exposure in AR development. The results emphasize the importance of considering both AR precision and efficiency when evaluating the perceptual limits of visual-spatial attention in children, particularly in time-limited tasks involving motion perception.

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Appendix A

Parent Consent Form

Research Project Title: **Visual Attention and Reading Study**
Principal Investigator and contact information: **Richard Kruk, (204) 474-7349**
Sponsor: **University of Manitoba**

Dear Parents or Guardians:

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

An important part of every child's early educational experience is learning to read. As a researcher in the Department of Psychology at the University of Manitoba, I am conducting a study to help us understand more about how children become mature readers. In particular I am studying how children's developing skills in visual attention and spoken language have an impact on learning to recognize printed letters and words. These are important dimensions of learning to read.

Children often acquire their reading abilities at different rates, and occasionally certain youngsters develop difficulties learning to read and write. Although the reasons for their problems are not always clearly understood, with a better understanding of how underlying skills develop in the first school years, and how they are related to learning to read, more effective methods of instruction can be developed for children, particularly those with reading difficulties.

The participation of your child is requested for a study that will examine the relationship between visual attention and reading skills. The study will take place at your child's school, and will involve two 40-minute sessions in a quiet room at the school. Your child's teacher will be asked to indicate the best days and times for your child to be involved in the sessions. During those sessions, each child will participate in several brief paper-and-pencil school-like tasks that involve language, vision, memory and reading. In addition, each child will participate in several computer-based visual games and reading-like tasks. The computer presentation will be both motivating and fun, as it is designed to be game-like. Our past experience with these tasks indicates that children very much enjoy playing with these computer "games" and experiencing the paper-and-pencil tasks. A researcher and a psychology student from the University who are carefully trained in working with children will conduct the study at the school.

All results will be kept in strict confidence to protect your child's anonymity; only researchers involved in the study will have access to results, organized using code numbers rather than children's names, and stored in a locked room at the University. Involvement in this research will not affect your child's work or progress at school. Any results that could be useful in developing effective reading instruction for individual children will be shared with you. At the end of the study, children will be given a short explanation of the study, and offered stickers and a chapter book as tokens of our appreciation.

With your support I hope that this research will bring us closer to a better understanding of reading in children. This is critical to a literate society like ours. When the study is complete, anticipated at about the summer of 2018, a report of the overall findings will be available at the school to interested teachers and parents, and on a web site dedicated to this project (www.earlyreadingproject.ca). Reading researchers will learn about the results in professional journals and conferences. A copy of the report of overall findings will be sent to you; please include your mail or email address on the attached form.

If you will allow your child to be included in this study, please detach and complete the form and return it to your child's teacher in the envelope provided within the next several days. Participation in this study is completely voluntary, and you and your child have the right to withdraw from the research at any time. I sincerely appreciate your cooperation. If you would like more information about the study please contact me at the Department of Psychology, University of Manitoba at 474-7349, or via email at Richard.Kruk@umanitoba.ca.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and /or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation. The University of Manitoba may look at the research records to see that the research is being done in a safe and proper way.

This research has been approved by the Psychology/Sociology Research Ethics Board, and by the school division. If you have any concerns or complaints about this project you may contact me, or the Human Ethics Coordinator (HEC) at (204) 474-7122 or the Human Ethics Coordinator (HEC) at 474-7122. A copy of this consent form has been given to you to keep for your records and reference.

Sincerely,

Richard Kruk, Ph.D.,
Associate Professor

Visual Attention and Reading Study
Parent/Guardian Consent Form

Richard Kruk, Dept. of Psychology
University of Manitoba

Name of Child (please print): ___________________________________

Child's Date of Birth: Month _____ Day _____ Year _____

CHECK HERE

____ I give permission for my child to participate in the study conducted by Richard Kruk.

____ I do NOT give permission for my child to participate in the study conducted by Richard Kruk.

If you are giving permission, please provide us with additional information in the attached questionnaire.

Signature of Parent/Guardian: ______________________ Date: ________________

Researcher's Signature: ___________________________ Date: ________________

If you are interested in receiving a copy of a report of the final results, please write your mailing or email address below:

____

We are planning to conduct a **follow-up study** involving a small number of children at the University. If you are willing to have your child considered for this follow-up study, please indicate:

_____ YES, I am willing to have my child considered for a follow-up study

_____ NO, I am NOT willing to have my child considered for a follow-up study

If you indicated YES, please provide the best way to contact you for the follow-up:

Telephone: ___________________ Email: ____________________________

Appendix B

Visual Attention and Reading Study
Parent Questionnaire

Please complete this questionnaire, as we would like to learn about your child and his/herreading and other experiences.

Name of child (please print): ____

Child's gender (circle): Male Female

Child's Age: ______________________________

Child's School: ____________________________

Child's Teacher:___________________________

Please circle the approximate number of days per week your child spends reading at home:
Weekdays: 0 1 2 3 4 5
Weekends: 0 1 2

On these days, please circle the approximate number of minutes per day spent reading:
Weekdays: None About 30 About 60 About 90 More than 90; please estimate _____
Weekends: None About 30 About 60 About 90 More than 90; please estimate _____

Please circle the approximate number of days per week your child spends playing *interactive* video games (games with rapidly moving objects/scenes):
Weekdays: 0 1 2 3 4 5
Weekends: 0 1 2

On these days, please circle the approximate number of minutes per day spent playing *interactive* video games (games with rapidly moving objects/scenes):

Weekdays: None About 30 About 60 About 90 More than 90; please estimate _____
Weekends: None About 30 About 60 About 90 More than 90; please estimate _____

Please see over …

Please indicate <u>your highest level of education</u>:<u>Other parent/guardian (if applicable)</u>:

___ Some High School	___ Some High School
___ High School	___ High School
___ Some post-secondary	___ Some post-secondary
___ Post-secondary diploma/degree	___ Post-secondary diploma/degree

Annual household income:
___ Less than $50,000
___ $50,000 or more

Home postal code: _______________________________

Is your child fluent in English?: Yes____ No_____

Language(s) spoken at home: _______________________________

Does your child require corrective lenses (eye glasses) for reading?: Yes____ No ____

Does your child have special needs that could have an impact on his/her school experience?:
Yes ____ No____

If yes, please specify the nature of the special need(s):
____ ADHD (attention deficit hyperactivity disorder that was diagnosed)
____ Speech Impediment (e.g. lisp)
____ Learning disability (e.g. reading disability, writing disability)
____ Other. Please specify the nature of the special need(s): ____________________

Number of brothers and/or sisters your child has:_____________________

Has your child received any formal additional reading help from school?:
Yes_____ No_____

Other than help from family members, has your child received any formal additional reading help outside of school (for example, a private tutor)?:
Yes_____ No_____

Appendix C

Script for the Attention Resolution Task, "Catching Fireflies"

[Title Screen: "Catching Fireflies."]

"We are going to play a game on the computer called Catching Fireflies."

[Press enter; show participant pictures of the 4 stages of a trial sequence]

"You will see 8 white dots in a small black square on the computer screen. These are fireflies glowing in the dark." [Point to Stage 1] *"One firefly is special. A red circle will flash around one firefly. Remember, this is the special firefly."* [Point to Stage 2; Press enter]

"Next, the red circle will go away and all of the dots will start moving around." [Point to Stage 3] *"You'll have to watch closely to follow the special firefly; it can be tricky to follow!"* [Press enter]

"After a while, the dots will stop moving. One of the dots will turn blue. Another dot will turn orange." [Point to Stage 4] *"One of these dots is the special firefly. You will tell me which one you think it is."* [Press enter]

"If you think the special firefly is the blue dot, say blue. If you think the special firefly is the orange dot, say orange. Do you understand?" [Press enter]

"Let's try it a few times. First, make sure to sit with your back up against the chair [ensure that participant is sitting in position]. *Watch closely for the red circle in the black square. You will have to keep your eyes open, so try to blink before the dots start moving. Are you ready?"*

[**First block: Press enter** to begin the practice trials.]
[**Second block: Press delete** to skip the practice trials. Experimental trials begin immediately.]

"Do you think the special firefly is the blue circle or the orange circle? It's okay to guess."

[Enter their response on the mouse. Press enter and provide feedback. Press enter to start the next practice trial. Repeat until participant completes 4 consecutive correct trials. The task is discontinued after a maximum of 16 practice trials.]

"Good work! Let's play the real game now. Remember to blink before the dots start moving. If your eyes get tired, ask for a break. Are you ready?"

[Continue with experimental trials. Feedback will now be provided on screen after every 6 trials. Provide verbal encouragement as well, e.g., ***'Good work! You got # fireflies!'***]

[Re-open the program to complete second block. Do another activity between blocks if desired.]

Appendix D

Pilot Study Abstract

Visual attention resolution involves the precision needed to visually select and focus on individual items in attentional space, permitting accurate individuation of visual components of the environment. We investigated the development of attention resolution precision and speed in twenty 7-year-old and twenty 11-year-old children. A computerized dot-tracking task requiring participants to follow a moving target among moving distractors in varying conditions of distance and speed, allowed measurement of attention resolution and modulation speed. Age differences in visual attention resolution and resolution-modulation speed were found, with 7-year-olds demonstrating lower d' sensitivity than 11-year-olds across manipulations of distance and speed. Results demonstrated a systematic progression in the development of attention resolution, and that speed of attention resolution modulation is an added aspect of visual attention resolution that improves across the sampled ages.

Appendix E

Child Assent Script

"We will be playing some games together. Some of these games will be on the computer, and some will be on paper. Are you ok with us doing these together?"

<PAUSE – WAIT FOR A YES OR NO ANSWER>

"If you don't feel you'd like to do a game, or at any time would like to stop, please say 'I want to stop.' We can go on to another game, or stop altogether. Are you ready to start?"

<PAUSE – WAIT FOR A YES OR NO ANSWER >

If the child says 'I want to stop,' or provides other indication of not wishing to continue with a task, the researcher will end the task in a positive way, saying: *"That's fine. Would you like to go on to another game, or stop altogether for today?"*

<PAUSE – WAIT FOR ANSWER >

If the child indicates interest in beginning the next task, the researcher will begin the next task. If the child indicates wishing to stop the session altogether, the child will be asked *"Would you like to continue another day?"*

<PAUSE – WAIT FOR A YES OR NO ANSWER >

If the child indicates "yes," then the child will be asked again to participate for the remaining tasks, the next available day. If "no," then no further participation will be sought, and the child will be provided with a short debriefing explanation of the purpose of the study. The child will be given debriefing and compensation, and will be escorted back to the classroom by the researcher. In the lab phase the exit protocol will be followed, with debriefing and compensation for participation provided.

Appendix F

Assessment of Response Bias

AR accuracy scores (proportion correct) were analyzed in a 2 x 2 x 2 x 2 x 3 mixed-design factorial ANOVA. Within-subjects factors included distance (close, far), speed (slow, fast), and target (orange, blue). Between-subjects factors included grade (2, 6) and reader group (below-average, average, above-average). The significant effects involving target are as follows:

Main effect of target: $F(1, 195) = 7.54$, $p = .007$.

Trials with orange targets ($M = .76$, $SE = .01$) obtained higher accuracy scores than trials with blue targets ($M = .73$, $SE = .01$).

Grade x Speed x Target: $F(1, 195) = 13.73$, $p < .001$.

Table F1

AR Accuracy by Grade, Speed, and Target Condition

	Grade 2		Grade 6	
Target colour	Slow speed (*SE*)	Fast speed (*SE*)	Slow speed (*SE*)	Fast speed (*SE*)
Orange	.73 (.01)	.59 (.01)	.92 (.01)	.78 (.02)
Blue	.68 (.02)	.60 (.01)	.92 (.02)	.72 (.02)

Grade x Distance x Speed x Target: $F(1, 195) = 8.48$, $p = .004$.

Table F2

AR Accuracy by Grade, Speed, Distance, and Target Condition

	Grade 2			
	Close distance		Far distance	
Target colour	Slow speed (*SE*)	Fast speed (*SE*)	Slow speed (*SE*)	Fast speed (*SE*)
Orange	.72 (.02)	.53 (.02)	.75 (.02)	.65 (.02)
Blue	.64 (.02)	.55 (.02)	.72 (.02)	.66 (.02)
	Grade 6			
	Close distance		Far distance	
	Slow speed (*SE*)	Fast speed (*SE*)	Slow speed (*SE*)	Fast speed (*SE*)
Orange	.89 (.02)	.70 (.02)	.93 (.02)	.86 (.02)
Blue	.91 (.02)	.60 (.02)	.94 (.02)	.85 (.02)

Grade x Reader Group x Target: $F(2, 195) = 2.89$, p = .058 (marginally significant).