Possible Mechanism of Audiovisual Temporal Integration Deficit in Developmental Dyslexia: Impaired Audiovisual Temporal Recalibration Ability

Authors: Runzhou Wang, Bi Hongyan, Bi Hongyan

Date: 2022-06-30T00:00:00+00:00

Abstract

The nature of developmental dyslexia has long been a focus of debate among researchers. Numerous studies have found that individuals with dyslexia exhibit deficits in audiovisual temporal integration. However, these studies have only examined the overall performance—namely, average-level performance—of audiovisual temporal integration processing in individuals with dyslexia, while neglecting to investigate the dynamic process of integration. Audiovisual temporal recalibration reflects the dynamic processing of audiovisual temporal integration; difficulties in recalibrating discrepancies between internal temporal representations and sensory inputs can impair multisensory integration, and individuals with dyslexia show deficits in recalibration-related abilities. Therefore, impaired audiovisual temporal recalibration ability may constitute the fundamental cause of audiovisual temporal integration deficits in developmental dyslexia. Future research should further investigate the specific manifestations of audiovisual temporal recalibration abilities in individuals with developmental dyslexia, as well as the underlying cognitive and neural mechanisms.

Full Text

A Possible Mechanism for Audiovisual Temporal Integration Deficits in Developmental Dyslexia: Impaired Audiovisual Temporal Recalibration Ability

WANG Runzhou, BI Hongyan
(CAS Key Laboratory of Behavioral Science; Center for Brain Science and Learning Difficulties, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China)

(Department of Psychology, University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract
The nature of developmental dyslexia has long been a focus of debate among researchers. Numerous studies have found that individuals with dyslexia exhibit deficits in audiovisual temporal integration. However, these studies have only examined the overall performance of audiovisual temporal integration processing in dyslexics—that is, performance at the average level—while neglecting to investigate the dynamic process of integration. Audiovisual temporal recalibration reflects the dynamic processing of audiovisual temporal integration; difficulty in recalibrating the discrepancy between internal temporal representations and sensory inputs leads to impaired multisensory integration, and individuals with dyslexia show deficits in recalibration-related abilities. Therefore, impaired audiovisual temporal recalibration ability may be the fundamental cause of audiovisual temporal integration deficits in developmental dyslexia. Future research needs to further examine the specific manifestations of audiovisual temporal recalibration ability in individuals with developmental dyslexia, as well as the cognitive and neural mechanisms underlying these manifestations.

Keywords: developmental dyslexia, audiovisual temporal integration, audiovisual temporal recalibration, dynamic processing, Bayesian theory

1 Introduction

The cultivation of reading ability is central to school education, and strong reading skills are crucial for individual development and the enhancement of national cultural literacy. However, some individuals exhibit reading abilities significantly below age-expected levels, a condition known as developmental dyslexia (DD). This disorder occurs when individuals with normal intelligence, adequate educational opportunity, and no visual or auditory impairments still struggle to acquire fluent reading (Casini et al., 2018). Dyslexia has widespread negative consequences, as children who experience reading failure often develop behavioral, social, academic, and psychological problems (Anthony & Lonigan, 2004). Therefore, exploring the fundamental nature of DD is a critical and urgent research topic with major theoretical and practical significance for early screening and subsequent intervention for individuals with DD.

Reading is a process that integrates information from visual and auditory channels (Pammer & Vidyasagar, 2005), and the ability to map correspondences between auditory speech and visual orthographic symbols is closely linked to reading ability (Ehri, 2005). Temporal factors—such as synchrony, duration, speed, and rhythmic structure—play important roles in integrating visual and auditory speech signals (Fujisaki et al., 2004; Van Wassenhove et al., 2007), and temporal integration forms the foundation of multisensory integration (Lewkowicz, 1992, 1994, 1996). Audiovisual temporal integration refers to the process by which individuals integrate temporally asynchronous audiovisual stimuli into a meaningful unified event (Stevenson et al., 2012; Stevenson & Wallace, 2013; 李涛涛 et al., 2018). The temporal binding window (TBW; Arrighi et al., 2006), along with metrics that reflect its size such as synchrony response probability (e.g., Francisco, Groen et al., 2017) and temporal perception thresholds (e.g., just noticeable difference; Mossbridge et al., 2017), can index audiovisual temporal integration ability. Because an appropriate audiovisual TBW is essential for correctly binding phonemes to characters during reading acquisition, audiovisual temporal integration constitutes a critical component of reading (Gori et al., 2020). Research has found that individuals with DD show impaired audiovisual temporal integration, typically manifested as an abnormally widened audiovisual TBW and difficulty disambiguating asynchronous stimuli—they perceive cross-modal stimuli as simultaneous even when the asynchrony is substantial (Francisco et al., 2014; Francisco, Jesse et al., 2017; Hairston et al., 2005; Virsu et al., 2003).

However, existing studies have only examined the overall—or average-level—performance of audiovisual temporal integration processing in individuals with DD (e.g., Francisco et al., 2014; Francisco, Jesse et al., 2017; Hairston et al., 2005; Laasonen et al., 2002; Virsu et al., 2003), without investigating the dynamic process of integration. Audiovisual temporal recalibration, as a process of dynamic adaptation to brief temporal delays between visual and auditory inputs, can capture this dynamic change: when asynchronous audiovisual stimuli are presented, the brain adjusts its perception of temporal synchrony toward the asynchrony—that is, toward the channel presented first—thereby facilitating perception as a unified event (Keetels & Vroomen, 2007; Van der Burg et al., 2013). Temporal recalibration during multisensory integration can also reflect dynamic changes in the TBW, including three phases: temporal window expansion, subjective simultaneity point (PSS) shift, and temporal window recovery (Navarra et al., 2005, 2007, 2009). Research on dyslexia has found that, at the behavioral level, individuals with DD show deficits in phonetic recalibration (Keetels et al., 2018). At the neural level, individuals with DD exhibit weaker neural adaptation than typical readers (Jaffe-Dax et al., 2018; Perrachione et al., 2016; Peter et al., 2019), and temporal recalibration is precisely an adaptive capacity for temporal asynchrony (Noel et al., 2017). Therefore, audiovisual temporal recalibration deficits may represent a more fundamental cognitive-neural mechanism underlying audiovisual temporal integration deficits in DD. This paper first systematically reviews research on audiovisual temporal integration deficits in DD. By analyzing limitations of existing studies and findings from related fields, we propose that impaired audiovisual temporal recalibration ability may constitute a more fundamental cognitive-neural mechanism. We then elaborate on the relationship between audiovisual temporal recalibration and integration, explaining how recalibration influences integration. Next, we review studies demonstrating impaired recalibration-related abilities in DD, providing evidence for potential audiovisual temporal recalibration deficits. Finally, we summarize the paper and propose directions for future research on audiovisual temporal recalibration in DD.

2.1 Behavioral Manifestations of Audiovisual Temporal Integration Deficits in Developmental Dyslexia

Virsu et al. (2003) employed two tasks to investigate the developmental trajectory of audiovisual temporal processing abilities in adults with DD from ages 20 to 59. In a temporal order judgment (TOJ) task, non-speech audiovisual stimuli were presented at various stimulus onset asynchronies (SOAs), and participants judged which modality appeared first. In a temporal processing acuity (TPA) task, participants judged whether cross-modal audiovisual stimuli were presented simultaneously. Both tasks used temporal perception thresholds to index audiovisual temporal integration ability. Results showed that regardless of age, individuals with DD exhibited significantly higher temporal perception thresholds than typical readers, and this processing deficit worsened with age (Virsu et al., 2003). Subsequently, Hairston et al. (2005) used a temporal ventriloquism task similar to TOJ tasks to examine the audiovisual temporal integration window in adults with dyslexia using non-speech stimuli. In this task, each trial contained two visual and two auditory stimuli. The first visual and auditory stimuli were presented simultaneously. The SOA between the second visual stimulus and the first visual stimulus was determined by each participant' s discrimination threshold and held constant. The SOA between the second auditory stimulus and the second visual stimulus varied randomly from 0 to 350 ms in 50 ms steps. The two visual stimuli appeared above and below a fixation point, and participants judged the location of the first visual stimulus. Results showed that in the control group, the facilitative effect of the second auditory stimulus on visual temporal order judgments disappeared when SOA exceeded 200 ms. In contrast, the dyslexia group still showed facilitative effects at an SOA of 350 ms, indicating a wider audiovisual TBW in individuals with dyslexia. The researchers argued that an expanded temporal integration window would impair the ability to quickly and accurately integrate cues from multiple sensory modalities. Specifically, during reading, the nervous system must appropriately map representations of visual elements (e.g., letters) onto corresponding auditory elements (e.g., phonemes). An expanded mapping window would lead to inappropriate correspondences, ultimately resulting in letter-phoneme mapping errors and decreased decoding speed and accuracy (Hairston et al., 2005).

Unlike previous studies that used only non-speech stimuli, Francisco et al. (2014) examined audiovisual temporal sensitivity in adults with dyslexia using both speech and non-speech stimuli. In a non-speech simultaneity judgment (SJ) task, participants judged whether a clapping action and clapping sound occurred simultaneously. In a speech-based McGurk synchrony judgment task, participants judged whether the syllable /apa/ and the visual articulation of /aka/ occurred simultaneously. The TBW, derived by fitting Gaussian functions to synchrony response probabilities across different SOAs, served as the index of audiovisual temporal integration ability. Results showed that compared to typical adults, adults with dyslexia exhibited a wider TBW when integrating speech audiovisual stimuli, indicating a deficit in audiovisual temporal integration for speech stimuli. However, no significant group difference emerged for non-speech audiovisual stimuli. The researchers suggested that the audiovisual temporal integration deficit in dyslexia represents a persistent state that continues into adulthood rather than a temporary developmental lag associated with reading acquisition. Regarding the lack of group differences for non-speech stimuli, they proposed two explanations: first, non-speech clapping stimuli may be simpler than speech stimuli, making synchrony judgments easier for individuals with dyslexia and thus eliminating group differences. Second, the task used differed from the temporal ventriloquism task employed by Hairston et al. (2005), which is based on order judgments. Order judgments focus on stimulus segregation and are more susceptible to response strategies, making them less accurate reflections of integration processing (Francisco et al., 2014).

Building on their 2014 study, Francisco, Jesse et al. (2017) recruited more adults with dyslexia and added a McGurk identification task, in which participants judged whether the syllable /apa/ and the visual articulation of /aka/ were perceived as /apa/, /aka/, or the fused syllable /ata/. Results showed that in both the McGurk synchrony judgment task with speech stimuli and the simultaneity judgment task with non-speech stimuli, individuals with dyslexia exhibited significantly wider audiovisual TBWs than typical readers. This indicated that they showed audiovisual temporal integration deficits not only for speech stimuli but also for more general non-speech stimuli. However, in the McGurk identification task, no significant difference in TBW emerged between individuals with dyslexia and typical readers. The researchers suggested that the abnormally widened TBW in dyslexia not only causes difficulty in learning letter-sound mappings but also reflects deficits in information sampling—that is, individuals with dyslexia may need an expanded TBW to compensate for sensory processing deficits. The dissociation between cross-modal speech synchrony judgment and speech perceptual fusion in dyslexia may relate to task nature and underlying processing mechanisms. Specifically, reading requires consciously mapping letter-sound correspondences and perceiving their synchrony. In contrast, the McGurk identification task involves automatic integration of information from two modalities into a unified percept. Thus, participants make implicit temporal synchrony judgments in the McGurk task but explicit judgments during reading. The core difficulty in acquiring letter-sound correspondences in dyslexia may therefore be the inability to make explicit temporal synchrony judgments, a deficit that the McGurk identification task, which involves implicit synchrony judgments, cannot detect (Francisco, Jesse et al., 2017).

Francisco, Groen et al. (2017) further expanded their sample and used the same three tasks to examine how audiovisual temporal sensitivity affects reading. This study used the mean probability of synchrony or fusion responses at each SOA as the temporal integration index, with higher response probabilities indicating wider TBWs. Surprisingly, results showed no significant differences between adults with dyslexia and typical readers across all three tasks. However, the researchers offered no explanation for these findings, which diverged from previous results (e.g., Francisco et al., 2014; Francisco, Jesse et al., 2017). Instead, they emphasized that audiovisual temporal sensitivity uniquely explained variance in reading performance, with more synchrony judgments associated with greater reading errors (Francisco, Groen et al., 2017). More recently, Wu Huiduo (2020) recruited Chinese children with DD and conducted a series of audiovisual temporal sensitivity studies, finding that children with DD exhibited wider audiovisual simultaneity windows than typical children in simultaneity judgment tasks. This indicates that Chinese children with DD show deficits in audiovisual temporal integration, consistent with findings from alphabetic writing systems.

Taken together, behavioral research demonstrates that individuals with dyslexia show weaker audiovisual temporal integration abilities than typical readers, a phenomenon that appears consistent across languages, ages, and stimulus types. Researchers have attempted to explain inconsistent findings by appealing to differences in experimental materials and task properties (e.g., Francisco et al., 2014; Francisco, Groen et al., 2017; Francisco, Jesse et al., 2017; Laasonen et al., 2002). For example, non-speech stimuli may be simpler and easier to judge than speech stimuli, thereby eliminating group differences (e.g., Francisco et al., 2014), and implicit temporal synchrony judgment tasks (McGurk identification) may fail to detect audiovisual temporal integration deficits (e.g., Francisco, Jesse et al., 2017). However, existing evidence does not fully support these explanations. Specifically, although the aforementioned studies found no significant differences in TBW between individuals with dyslexia and typical readers in McGurk identification tasks (e.g., Francisco, Groen et al., 2017; Francisco, Jesse et al., 2017), Woynaroski et al. (2013) successfully detected audiovisual temporal integration deficits using McGurk identification tasks. This indicates that task differences are not the essential cause of discrepant findings. Moreover, these explanations cannot account for why different results emerge using identical materials and tasks (e.g., Francisco, Groen et al., 2017 vs. Francisco, Jesse et al., 2017; Hairston et al., 2005 vs. Laasonen et al., 2002). These controversies suggest that key factors influencing audiovisual temporal integration deficits in DD remain unidentified. Previous research has found that normal average-level multisensory integration performance can mask underlying deficits in integration processing (e.g., Noel et al., 2017; Zaidel et al., 2015). Furthermore, temporal recalibration indices that reflect integration processing are more sensitive than global measures like TBW in detecting differences in audiovisual temporal integration ability (e.g., Noel et al., 2017). These findings suggest that regardless of whether individuals with DD show deficits in average-level audiovisual temporal integration, they may exhibit deficits in audiovisual temporal recalibration that reflects the integration process. We will further discuss this issue in Section 2.3.

2.2 Neural Manifestations of Audiovisual Temporal Integration Deficits in Developmental Dyslexia

Froyen et al. (2011) used EEG to examine cross-modal processing of letter-speech sound associations in children with dyslexia, using mismatch negativity (MMN) as the index. Visual stimuli were the letter "a,"auditory standard stimuli were the phoneme "/a/" (85%), and auditory deviant stimuli were the phoneme "/o/" (15%). In the auditory unimodal condition, only auditory standard and deviant stimuli were presented. In the cross-modal audiovisual condition, stimuli were presented in two ways: simultaneously or with the visual stimulus preceding the auditory stimulus by 200 ms. Using a passive task, participants responded to randomly presented probe stimuli at the center of the screen to maintain attention. Results showed that typical children exhibited significantly larger MMN amplitudes in the asynchronous audiovisual condition than in the auditory unimodal condition, whereas children with dyslexia showed no significant difference between these conditions, indicating difficulty automatically integrating letters and speech sounds (Froyen et al., 2011). Using a similar paradigm, Mittag et al. (2013) found that typical adults showed significantly larger MMN amplitudes in the synchronous than in the asynchronous audiovisual condition, whereas adults with dyslexia showed no significant difference between conditions, suggesting that audiovisual temporal integration deficits in DD persist into adulthood.

fMRI studies have identified brain regions involved in audiovisual temporal integration, including bilateral frontoparietal networks, superior temporal cortex (STC), and visual and auditory cortices (e.g., Adhikari et al., 2013; Binder, 2015; Dhamala et al., 2007; Noesselt et al., 2007). Following cross-modal temporal synchrony training, resting-state functional connectivity between the posterior superior temporal sulcus (pSTS) and visual and auditory cortices is significantly enhanced (Powers et al., 2012). However, existing fMRI research on dyslexia has focused on integration of simultaneous orthographic-phonological stimuli (e.g., Blau et al., 2009, 2010; Rüsseler et al., 2018) rather than temporal integration ability. Nevertheless, a review (Stevenson et al., 2016) noted that groups who commonly show audiovisual temporal integration deficits (e.g., autism spectrum disorder, ASD) also exhibit neural deficits in multisensory temporal integration localized to the pSTS. Therefore, audiovisual temporal integration deficits may be associated with abnormal activation in visual, auditory, and temporal cortices.

2.3 Limitations of Current Research on Audiovisual Temporal Integration in Developmental Dyslexia

Research indicates that the audiovisual TBW is not fixed during integration processing but changes dynamically, including three phases: temporal window expansion, subjective simultaneity point shift, and temporal window recovery—collectively known as temporal recalibration (Navarra et al., 2005, 2007, 2009).

This expansion and contraction of the temporal window depends on the influence of prior sensory experience (Powers et al., 2009), and temporal recalibration can occur within a short timeframe (e.g., a single trial), known as rapid temporal recalibration (Van der Burg et al., 2013). However, current behavioral research on audiovisual temporal integration in DD has calculated TBW and related indices based on mean performance across all trials under different experimental conditions (e.g., Francisco et al., 2014; Francisco, Jesse et al., 2017; Hairston et al., 2005; Laasonen et al., 2002; Virsu et al., 2003), and neural research has compared overall averaged brain activation across conditions (e.g., Froyen et al., 2011; Mittag et al., 2013). These approaches can only examine overall—or average-level—performance of audiovisual temporal integration processing in DD and cannot probe the dynamic changes in integration processing.

De Niear et al. (2017) found that in typical individuals, the TBW narrows significantly as an experiment progresses. This progressive narrowing of the TBW during audiovisual temporal integration has been confirmed by numerous training studies. After a single session of feedback-based audiovisual simultaneity judgment training, individuals show significant TBW narrowing, demonstrating the plasticity of TBW during audiovisual temporal integration (e.g., Powers et al., 2009, 2012; Theves et al., 2020). Additionally, Noel et al. (2016) noted that rapid temporal recalibration is intrinsically linked to audiovisual temporal integration and can influence the formation of temporal integration representations (the integration window). Therefore, the essence of the abnormally widened audiovisual integration window in DD observed in previous research may be difficulty reshaping TBW size through rapid temporal recalibration during integration processing—that is, a deficit in rapid audiovisual temporal recalibration.

Furthermore, research has shown that even when individuals exhibit intact multisensory integration performance at the average level, the integration process itself may be abnormal. Zaidel et al. (2015) examined multisensory integration of visual and vestibular cues in individuals with ASD. In a dark environment, participants stood on a platform moving at different angles toward the left or right front, while visual stimuli consisted of randomly moving light dots (pure noise). Participants judged whether they were moving toward the left or right front. The experiment comprised four similar blocks to assess multisensory integration ability at different stages. When integration performance across all four blocks was treated as a whole and average-level performance was compared, individuals with ASD showed no significant difference in integration thresholds compared to typical individuals, suggesting intact multisensory integration ability. However, when the four blocks were compared separately, individuals with ASD showed better integration performance than typical individuals in the initial stage. Typical individuals demonstrated significant learning effects as the experiment progressed, achieving optimal integration in the fourth block, whereas individuals with ASD showed no significant change in integration performance over time. Further analysis revealed that typical individuals progressively reduced the weighting of visual channel information, whereas individuals with ASD did not show this pattern. The researchers concluded that multisensory integration deficits in ASD stem from attenuated prior knowledge, leading to a tendency to perceive the world based primarily on current sensory input rather than in the context of past sensory experience. Because the visual stimuli were pure noise, individuals with ASD better perceived and integrated current stimuli during the initial stage, whereas prior sensory experience interfered with integration processing in typical individuals. As the experiment progressed, typical individuals flexibly calibrated their multisensory integration based on accumulated experience, whereas the processing strategy of individuals with ASD remained static and difficult to adjust flexibly according to prior sensory experience (Zaidel et al., 2015). Similarly, Noel et al. (2017) used a simultaneity judgment task to examine rapid audiovisual temporal recalibration in individuals with ASD. Although individuals with ASD showed no significant difference in TBW compared to typical individuals when integrating non-speech stimuli, the shift in subjective simultaneity point (ΔPSS), which reflects rapid audiovisual temporal recalibration ability, was significantly smaller than in typical individuals, indicating a rapid audiovisual temporal recalibration deficit in ASD (Noel et al., 2017). These findings demonstrate that normal average-level multisensory integration performance can mask recalibration deficits in the integration process. Although this evidence comes from individuals with ASD, both ASD and DD are neurodevelopmental disorders, and individuals with ASD also show reading impairments (e.g., O' Connor & Klein, 2004; Patti & Lupinetti, 1993). In Noel et al.' s (2017) study, individuals with ASD also scored significantly lower than typical individuals on vocabulary tests related to reading. Moreover, the behavioral manifestations and neural bases of audiovisual temporal integration deficits in ASD share many similarities with those in DD (for review, see Zhou, Cheung, & Chan, 2020). Therefore, findings from ASD research can inform DD research. Additionally, a recent study on typical populations found that although adolescents and adults showed no difference in TBW size, which reflects average-level audiovisual temporal integration, adolescents exhibited weaker rapid audiovisual temporal recalibration ability than adults (Zhou, Shi et al., 2020). In summary, these findings indicate that: (1) normal overall multisensory integration performance, or normal average-level performance, can mask deficits in the integration process; and (2) temporal recalibration indices that reflect integration processing are more sensitive than global measures like TBW in detecting differences in audiovisual temporal integration ability. This provides a plausible explanation for previous studies that failed to find abnormally widened TBW in individuals with DD at the average level (e.g., Francisco et al., 2014; Francisco, Groen et al., 2017; Francisco, Jesse et al., 2017; Laasonen et al., 2002)—namely, that normal TBW indices in individuals with DD may mask deficits in rapid audiovisual temporal recalibration that reflect impaired processing.

3 The Relationship Between Audiovisual Temporal Recalibration and Audiovisual Temporal Integration

A necessary condition for multisensory integration is that cross-modal paired stimuli maintain temporal synchrony (Meredith et al., 1987; 袁祥勇, 黄希庭, 2011). Superficially, it might appear that only cross-modal information presented simultaneously can elicit multisensory integration. However, physical transmission speeds differ between visual and auditory stimuli (e.g., light travels much faster than sound in air), preventing simultaneous arrival at sensory organs; moreover, neural conduction is faster for auditory than visual stimuli (Vroomen & Keetels, 2010). Consequently, even simultaneously presented audiovisual stimuli are subject to temporal delays at the sensory level. To address this issue, multisensory temporal processing has evolved to be highly dynamic, allowing adaptive adjustment to different sensory inputs (for a review, see Vroomen & Keetels, 2010). Specifically, audiovisual temporal processing flexibly changes based on prior sensory experience. When individuals are exposed to asynchronous audiovisual environments, the subjective simultaneity point shifts toward the modality presented first, thereby reducing perceived asynchrony (Fujisaki et al., 2004). This process is known as audiovisual temporal recalibration (e.g., Van der Burg et al., 2015), commonly indexed by the shift in subjective simultaneity point between visual-leading and auditory-leading conditions (e.g., Harvey et al., 2014; Noel et al., 2017) and changes in TBW (e.g., De Niear et al., 2017; Noel et al., 2016; Zhou, Shi et al., 2020). Its function is to reduce the impact of inter-stimulus delays on multisensory integration through temporal recalibration, reflecting the temporal plasticity of multisensory integration (Yu et al., 2009). The ultimate effect is to re-perceive temporally asynchronous cross-modal stimuli as simultaneous—that is, to reshape simultaneity perception (袁祥勇, 黄希庭, 2011). Moreover, rapid audiovisual temporal recalibration, as a form of short-term plasticity representing the capacity to adapt quickly to environmental changes, plays an important role in audiovisual temporal integration (Noel et al., 2017). Research has found significant correlations between individuals' rapid audiovisual temporal recalibration ability and their audiovisual temporal integration ability (Harvey et al., 2014; Van der Burg et al., 2013). A cross-sectional study (Noel et al., 2016) revealed that individuals' temporal integration abilities for both speech and non-speech audiovisual stimuli were significantly correlated with their corresponding rapid temporal recalibration abilities, and that rapid audiovisual temporal recalibration ability matures earlier than audiovisual temporal integration ability. The researchers proposed that because audiovisual temporal recalibration and integration abilities are intrinsically linked, rapid audiovisual temporal recalibration—a dynamic processing mechanism—can influence the formation of more stable temporal integration representations (Noel et al., 2016).

The influence of multisensory recalibration on multisensory integration can also be explained by Bayesian theory. A study published in *Nature* (Ernst & Banks, 2002) found that predictions from a Bayesian model using individuals' unimodal visual or haptic height estimates closely matched their performance in visuo-haptic integration experiments, suggesting that human cross-modal information integration follows optimal Bayesian statistical principles (Ernst & Banks, 2002). Within the Bayesian framework, the brain estimates the reliability of information from different modalities by perceiving relationships between them, then uses these prior expectations to compare with current sensory inputs and adjusts the weighting of each modality during multisensory integration to optimize decision-making (Figure 1 [Figure 1: see original paper]; Ernst & Bülthoff, 2004). Temporal recalibration can be viewed as a dynamic processing mechanism that adapts to temporal asynchrony between cross-modal stimuli, allowing individuals to re-establish stable prior knowledge about temporal relationships in dynamic contexts, which in turn influences subsequent multisensory integration under different temporal relationships (Noel et al., 2016; Sato & Aihara, 2011; 袁祥勇 et al., 2012). Specifically, established prior knowledge generates top-down predictions, and the discrepancy between these internally generated predictions and current sensory inputs can be minimized through recalibration, thereby optimizing integration (Noel et al., 2017). Regarding how abnormal recalibration processing impairs multisensory integration, a review by Pellicano and Burr (2012) proposed that attenuated prior knowledge leads to a tendency to perceive the world based primarily on currently incoming sensory information rather than in the context of past sensory experience. This may explain abnormal performance in special populations (e.g., ASD) during multisensory integration processing. Specifically, impaired multisensory recalibration ability weakens representations of prior knowledge. This attenuation of prior knowledge assigns greater weight to currently incoming sensory cues, making individuals more reliant on current sensory information for judgments. Meanwhile, without sufficient sensory references for comparison, individuals become less able to recalibrate discrepancies between internal representations and sensory inputs, further impairing multisensory integration processing (Noel et al., 2017). In summary, individuals with impaired audiovisual temporal recalibration ability may have difficulty calibrating discrepancies between existing internal representations and current sensory inputs regarding cross-modal temporal relationships during dynamic audiovisual temporal integration processing, thereby affecting the formation of a stable TBW. Because an abnormal audiovisual TBW impairs the brain's ability to integrate visual and auditory stimuli, blurring letter-speech sound pairings and consequently affecting reading, rapid audiovisual temporal recalibration deficits may represent a more fundamental cognitive-neural mechanism underlying audiovisual temporal integration deficits in DD.

Figure 1. Sensory-action loop within the Bayesian framework (adapted from Ernst & Bülthoff, 2004).

4 Studies on Recalibration-Related Abilities in Developmental Dyslexia

No study has directly examined audiovisual temporal recalibration ability in individuals with DD, but previous research on recalibration-related abilities can provide evidence for potential deficits. At the behavioral level, studies have found phonetic recalibration deficits in individuals with DD. Keetels et al. (2018) recruited adults with dyslexia to examine their phonetic recalibration ability. The researchers created a nine-item continuum (A1-A9) by manipulating the second formant of consonant syllables /aba/ and /ada/. Visual stimuli were three letters: "aba" (Vb) or "ada" (Vd). The experiment first presented eight consecutive letter-sound combinations (e.g., VbA1), followed by three ambiguous sounds (A4, A5, A6) each presented twice, and participants judged whether each sound was closer to /aba/ or /ada/. Results showed that after exposure to ambiguous letter-sound combinations (e.g., VbA5 or VdA5), the dyslexia group showed significantly weaker recalibration than the control group. When consonant syllables were replaced with vowel syllables, the dyslexia group again showed significantly weaker recalibration. These findings indicate that individuals with dyslexia exhibit phonetic recalibration deficits at the speech level, which may cause difficulties in learning and applying letter-sound associations (Keetels et al., 2018). Recently, Ozernov-Palchik et al. (2021) used a similar paradigm and found that this phonetic adaptation ability was significantly weaker in both children and adults with DD compared to age-matched typical individuals. Because temporal processing forms the perceptual foundation of speech processing (Kotz & Schwartze, 2010) and abnormal cross-modal temporal processing interferes with building letter-speech sound pairings (Francisco et al., 2014; Froyen et al., 2008; Wallace & Stevenson, 2014; Zhou, Cheung, & Chan, 2020), findings on phonetic recalibration deficits in DD can indirectly support the existence of audiovisual temporal recalibration deficits in this population. Additionally, Gori et al. (2020) used a temporal bisection task to examine temporal representations of multisensory stimuli in children with DD. Each trial contained three pairs of audiovisual stimuli presented sequentially at different SOAs, and participants judged whether the second pair was temporally closer to the first or third pair. Results showed that children with dyslexia exhibited significant deviations from Bayesian model predictions when the second pair was visual-leading, and these deviations were greater than in typical children (Gori et al., 2020). This reflects that individuals with dyslexia cannot integrate cross-modal audiovisual temporal information according to optimal Bayesian statistical principles. Based on the Bayesian prior attenuation theory (e.g., Noel et al., 2017; Pellicano & Burr, 2012), we can speculate that this may result from difficulty recalibrating discrepancies between internal temporal representations and sensory inputs, leading to impaired audiovisual temporal integration.

At the neural level, research has found that even when identical audiovisual stimuli are repeatedly presented, individuals with dyslexia show persistently high brain activation levels, a phenomenon observed during processing of both speech and non-speech audiovisual stimuli (Perrachione et al., 2016). The researchers interpreted this as reduced rapid neural adaptation to cross-modal audiovisual stimuli in dyslexia (Perrachione et al., 2016). A subsequent study by Jaffe-Dax et al. (2018) found that brain regions associated with reduced rapid adaptation in DD are located in the left superior temporal cortex, including auditory cortex—areas that correspond to those involved in audiovisual temporal integration (e.g., Dhamala et al., 2007; Noesselt et al., 2007). Because individuals with DD show weaker rapid neural adaptation than typical readers and rapid temporal recalibration represents rapid adaptation to temporal asynchrony, this suggests that rapid audiovisual temporal recalibration ability may be impaired in individuals with DD.

5 Summary and Outlook

In summary, previous research has demonstrated that individuals with dyslexia show weaker audiovisual temporal integration abilities than typical readers at both behavioral and neural levels. This phenomenon appears consistent across languages, ages, and stimulus types, representing a pervasive impairment that supports the existence of audiovisual temporal integration deficits in DD. However, current behavioral research on audiovisual temporal integration deficits in DD has calculated TBW and related indices based on mean performance across all trials under different experimental conditions, and neural research has compared overall averaged brain activation across conditions. These approaches can only examine overall—or average-level—performance of audiovisual temporal integration processing and cannot investigate the dynamic process of integration, making it difficult to reveal the essence of audiovisual temporal integration deficits in DD. Research on audiovisual temporal recalibration, which reflects the integration process, can address this limitation. Temporal recalibration reflects the dynamic process of adapting to different asynchronies—that is, it influences subsequent multisensory integration by re-establishing stable prior knowledge about temporal relationships. Impaired multisensory recalibration ability weakens representations of prior knowledge. According to the Bayesian prior attenuation theory, attenuated prior knowledge leaves individuals without sufficient sensory references to compare with current inputs, making it difficult to recalibrate discrepancies between internal representations and sensory inputs and thereby impairing multisensory integration. Furthermore, research in other domains has found that normal average-level audiovisual temporal integration performance can mask rapid audiovisual temporal recalibration deficits that reflect abnormal integration processing. Therefore, more fundamental deficits in audiovisual temporal recalibration ability may underlie audiovisual temporal integration deficits in DD. Currently, no study has directly explored audiovisual temporal recalibration ability in individuals with DD. Future research can proceed in the following directions.

5.1 Manifestations of Audiovisual Temporal Recalibration Ability Across Different Timescales in Developmental Dyslexia

Van der Burg et al. (2015) investigated whether long-term adaptation-induced audiovisual temporal recalibration and rapid audiovisual temporal recalibration represent shared or independent processes. The experiment first presented participants with audiovisual stimuli at a fixed asynchrony for 3 minutes (adaptation phase), after which participants completed an audiovisual simultaneity judgment task (test phase). Results showed that in the test phase, the channel order of audiovisual stimuli in the preceding trial caused a significant shift in the subjective simultaneity point of the current trial, indicating rapid audiovisual temporal recalibration. However, this shift did not change significantly over time, suggesting that rapid audiovisual temporal recalibration effects remained constant throughout the test phase. For long-term adaptation-induced recalibration, the shift in subjective simultaneity point changed significantly over time, with recalibration effects gradually decaying. These results demonstrate that audiovisual temporal recalibration is influenced by both the channel order of audiovisual stimuli in the preceding trial of the test phase and the channel order during the adaptation phase, and that long-term adaptation-induced and rapid audiovisual temporal recalibration are independent processes (Van der Burg et al., 2015). To date, only studies examining rapid audiovisual temporal recalibration in ASD exist. Research by Turi et al. (2016) and Noel et al. (2017) found that individuals with ASD cannot perform rapid temporal recalibration for simple, non-speech audiovisual asynchronous stimuli. Future research should examine audiovisual temporal recalibration ability across different timescales in individuals with DD. Based on the above findings, we hypothesize that individuals with DD exhibit audiovisual temporal recalibration deficits at both timescales, showing reduced influence of long-term adaptation contexts and preceding trial channel order on audiovisual temporal integration, with significantly smaller shifts in subjective simultaneity point and/or changes in TBW compared to typical readers.

5.2 Dynamic Changes in Audiovisual Temporal Integration Window and Recalibration Effects in Developmental Dyslexia

The audiovisual temporal integration window changes dynamically during integration processing (Navarra et al., 2005, 2007, 2009). Research on ASD, which also exhibits audiovisual temporal integration deficits, has found that individuals with ASD perform well in the initial stage of multisensory integration tasks. However, over time, they have difficulty adjusting multisensory integration processing based on prior sensory experience, leading to poorer integration performance in later stages compared to typical populations (Zaidel et al., 2015). Previous findings that individuals with dyslexia show no difference in average TBW size from typical readers may be because good initial integration performance masks deficits in subsequent processing stages. Future research could adopt the sliding window method used by Van der Burg et al. (2015) and De

Niear et al. (2017) to fit Gaussian curves trial-by-trial, obtaining TBW and subjective simultaneity point shifts that change continuously throughout the experiment, thereby examining the temporal dynamics of audiovisual temporal integration window and recalibration effects in individuals with DD. Based on existing findings, we hypothesize that: (1) In the initial experimental stage, TBW width in individuals with DD will not differ significantly from, or may even be narrower than, that of typical readers; as the experiment progresses, TBW width in individuals with DD will gradually exceed that of typical readers. (2) For long-term adaptation-induced recalibration effects, recalibration in individuals with DD will decay more rapidly over time compared to typical readers. (3) For rapid audiovisual temporal recalibration effects, neither individuals with DD nor typical readers will show significant changes over time, but rapid recalibration effects will remain at lower levels in individuals with DD.

5.3 Neural Basis of Audiovisual Temporal Recalibration Deficits in Developmental Dyslexia

Simon et al. (2017, 2018) examined the neural basis of rapid audiovisual temporal recalibration over time using simultaneity judgment tasks with speech or non-speech stimuli. They found that event-related potentials (ERPs) in the current trial were modulated by the channel order of audiovisual stimuli in the preceding trial. Specifically: (1) When the SOA between visual and auditory stimuli was small (e.g., 300 ms), ERP amplitudes around 125 ms after the second stimulus in the current trial, recorded from central and parietal regions, were influenced by the channel order of the preceding trial, with significantly lower amplitudes for channel-consistent than channel-inconsistent conditions. This suggests that recalibration of stimuli with short asynchronies can occur in high-level cognitive processes related to stimulus evaluation and decision-making (Simon et al., 2017). (2) When the SOA between visual and auditory stimuli was large (e.g., 450 ms), ERP amplitudes around 300 ms after the first stimulus in the current trial were similarly influenced by the channel order of the preceding trial, with significantly lower amplitudes for channel-consistent than channel-inconsistent conditions. This indicates that when the SOA is sufficiently large, neural adaptation can also occur in early sensory processing before the second stimulus appears (Simon et al., 2018). However, because individuals with DD lack rapid neural adaptation ability (e.g., Jaffe-Dax et al., 2018; Perrachione et al., 2016; Peter et al., 2019), experimental materials used in traditional simultaneity judgment tasks cannot be directly applied to dyslexia research. Repeated presentation of identical stimuli cannot determine whether results reflect rapid audiovisual temporal recalibration deficits or simply deficits in adapting to repeated stimuli. Research has found that rapid audiovisual temporal recalibration is primarily driven by fundamental temporal factors—it occurs even when audiovisual stimuli differ between trials or when sources are mismatched (e.g., a female face paired with a male voice; Van der Burg & Goodbourn, 2015). Therefore, future research on DD could use different audiovisual stimulus combinations to control for deficits in adapting to repeated stimuli. We hypothesize that ERP amplitudes evoked by current trials in individuals with DD will be less influenced by the channel order of audiovisual stimuli in preceding trials, reflecting rapid audiovisual temporal recalibration deficits. Furthermore, brain structural and functional research has found that the medial parietal cortex serves as a neural hub that maintains modality-specific sensory representations and flexibly links past and current information to guide adaptive behaviors like audiovisual recalibration (Park & Kayser, 2019). Additionally, audiovisual cross-modal phonetic recalibration is accompanied by significant activation in temporal cortex, parietal cortex, insula, and motor regions (Ullas et al., 2020). Therefore, the neural basis of audiovisual temporal recalibration deficits in DD may involve structural and functional impairments in these brain regions.

5.4 Relationship Between Audiovisual Temporal Recalibration Ability and Reading in Developmental Dyslexia

Research has found significant correlations between audiovisual temporal recalibration ability and audiovisual temporal integration ability (Harvey et al., 2014; Noel et al., 2016; Van der Burg et al., 2013). Furthermore, typical readers' audiovisual temporal integration ability can influence reading through rapid naming and orthographic skills (Liu et al., 2019), suggesting that audiovisual temporal recalibration ability may also indirectly affect reading through these reading-related cognitive skills. A key causal factor in dyslexia is poor ability to sequence letters and their sounds, leading to slower letter recognition (Vidyasagar & Pammer, 2010), and this rapid temporal processing deficit also impairs letter position and overall orthographic perception, causing problems in learning grapheme-phoneme correspondences (Hood & Conlon, 2004). Temporal recalibration can continuously form new prior knowledge by receiving new temporal relationships (e.g., delays between audiovisual stimuli), which in turn influences subsequent temporal order perception (Sato & Aihara, 2011). Moreover, the initial expansion of TBW during temporal recalibration reflects the brain' s ability to reduce discomfort from sequentially presented sensory stimuli by lowering temporal order judgment resolution, thereby facilitating integrated perception and memory (袁祥勇, 黄希庭, 2011). Therefore, if individuals with DD have deficits in audiovisual temporal recalibration ability, this would affect their rapid temporal processing and audiovisual integration abilities, leading to difficulties in phonological processing, rapid naming, orthographic processing, and ultimately reading impairment. In summary, examining the relationship between audiovisual temporal recalibration ability and reading in DD will help us better understand the fundamental nature of dyslexia.

5.5 Causal Relationship Between Developmental Dyslexia and Audiovisual Temporal Recalibration Deficits

If individuals with DD exhibit deficits in audiovisual temporal recalibration ability, does this deficit cause DD, or does it result from failure to acquire reading and low reading proficiency? Liu et al. (2019) found that audiovisual cross-modal temporal integration ability influences reading through different pathways in individuals with dyslexia versus typical readers: in typical readers, audiovisual cross-modal temporal integration influences reading through rapid naming and orthographic skills, whereas this pathway does not exist in individuals with dyslexia (Liu et al., 2019). However, data-driven path analysis alone cannot establish causality. The most convincing method to demonstrate that audiovisual temporal recalibration deficits cause dyslexia would be to show that interventions improving rapid audiovisual temporal recalibration ability also enhance reading ability. Notably, De Niear et al. (2017) used a simultaneity judgment task to explore the role of feedback signals in rapid audiovisual temporal recalibration. They found that participants showed stronger rapid audiovisual temporal recalibration when receiving feedback compared to no-feedback conditions, indicating that feedback signals maintain and facilitate rapid audiovisual temporal recalibration during rapid trial-to-trial learning (De Niear et al., 2017). Therefore, using feedback-based audiovisual simultaneity judgment tasks as training programs may be an effective method for improving audiovisual temporal recalibration ability. We can hypothesize that populations with audiovisual temporal recalibration deficits would benefit from feedback-based audiovisual temporal recalibration training, with potential for improving higher-level cognitive functions such as reading. Thus, applying audiovisual temporal recalibration training to individuals with DD could help clarify the causal relationship between audiovisual temporal recalibration deficits and DD while potentially developing an intervention for dyslexia.

References

李涛涛, 胡金生, 王琦, 李骋诗, 李松泽, 何建青, …刘淑清. (2018). 孤独症谱系障碍者的视听时间整合. 心理科学进展, 26(6), 1031–1040.

武慧多. (2020). 发展性阅读障碍儿童视听时间敏感性及其对阅读能力的影响 (博士学位论文). 华东师范大学.

袁祥勇, 黄希庭. (2011). 多感觉整合的时间再校准. 心理科学进展, 19(5), 692–700.

袁祥勇, 黄希庭, 毕翠华, 袁宏. (2012). 视听时间再校准: 适应空间与适应客体的联合及独立作用. 心理学报, 44(2), 143–153.

Adhikari, B. M., Goshorn, E. S., Lamichhane, B., & Dhamala, M. (2013). Temporal-order judgment of audiovisual events involves network activity between parietal and prefrontal cortices. *Brain Connectivity, 3*(5), 536–545.

Anthony, J. L., & Lonigan, C. J. (2004). The nature of phonological awareness: Converging evidence from four studies of preschool and early grade school children. *Journal of Educational Psychology, 96*(1), 43–55.

Arrighi, R., Alais, D., & Burr, D. (2006). Perceptual synchrony of audiovisual streams for natural and artificial motion sequences. *Journal of Vision, 6*(3), 260–268.

Binder, M. (2015). Neural correlates of audiovisual temporal processing-comparison of temporal order and simultaneity judgments. *Neuroscience, 300*, 432–447.

Blau, V., Reithler, J., van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R., & Blomert, L. (2010). Deviant processing of letters and speech sounds as proximate cause of reading failure: A functional magnetic resonance imaging study of dyslexic children. *Brain, 133*(3), 868–879.

Blau, V., van Atteveldt, N., Ekkebus, M., Goebel, R., & Blomert, L. (2009). Reduced neural integration of letters and speech sounds links phonological and reading deficits in adult dyslexia. *Current Biology, 19*(6), 503–508.

Casini, L., Pech-Georgel, C., & Ziegler, J. C. (2018). It's about time: Revisiting temporal processing deficits in dyslexia. *Developmental Science, 21*(2), e12530. https://doi.org/10.1111/desc.12530

De Niear, M. A., Noel, J. P., & Wallace, M. T. (2017). The impact of feedback on the different time courses of multisensory temporal recalibration. *Neural Plasticity, 2017*, 3478742. https://doi.org/10.1155/2017/3478742

Dhamala, M., Assisi, C. G., Jirsa, V. K., Steinberg, F. L., & Kelso, J. S. (2007). Multisensory integration for timing engages different brain networks. *NeuroImage, 34*(2), 764–773.

Ehri, L. C. (2005). Learning to read words: Theory, findings, and issues. *Scientific Studies of Reading, 9*(2), 167–188.

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature, 415*(6870), 429–433.

Ernst, M. O., & Bülthoff, H. H. (2004). Merging the senses into a robust percept. *Trends in Cognitive Sciences, 8*(4), 162–169.

Francisco, A. A., Groen, M. A., Jesse, A., & McQueen, J. M. (2017). Beyond the usual cognitive suspects: The importance of speechreading and audiovisual temporal sensitivity in reading ability. *Learning and Individual Differences, 54*, 60–72.

Francisco, A. A., Jesse, A., Groen, M. A., & McQueen, J. M. (2017). A general audiovisual temporal processing deficit in adult readers with dyslexia. *Journal of Speech, Language, and Hearing Research, 60*(1), 144–158.

Francisco, A. A., Jesse, A., & McQueen, J. M. (2014, September). Audiovisual temporal sensitivity in typical and dyslexic adult readers. In *Interspeech 2014: 15th Annual Conference of the International Speech Communication Association* (pp. 2575–2579), Singapore.

Froyen, D., van Atteveldt, N., Bonte, M., & Blomert, L. (2008). Cross-modal enhancement of the MMN to speech-sounds indicates early and automatic integration of letters and speech-sounds. *Neuroscience Letters, 430*(1), 23–28.

Froyen, D., Willems, G., & Blomert, L. (2011). Evidence for a specific cross-modal association deficit in dyslexia: An electrophysiological study of letter-speech sound processing. *Developmental Science, 14*(4), 635-648.

Fujisaki, W., Shimojo, S., Kashino, M., & Nishida, S. Y. (2004). Recalibration of audiovisual simultaneity. *Nature Neuroscience, 7*(7), 773-778.

Gori, M., Ober, K. M., Tinelli, F., & Coubard, O. A. (2020). Temporal representation impairment in developmental dyslexia for unisensory and multisensory stimuli. *Developmental Science, 23*(3), e12977. https://doi.org/10.1111/desc.12977

Hairston, W. D., Burdette, J. H., Flowers, D. L., Wood, F. B., & Wallace, M. T. (2005). Altered temporal profile of visual-auditory multisensory interactions in dyslexia. *Experimental Brain Research, 166*(3-4), 474-480.

Harvey, C., van der Burg, E., & Alais, D. (2014). Rapid temporal recalibration occurs crossmodally without stimulus specificity but is absent unimodally. *Brain Research, 1585*, 120-130.

Hood, M., & Conlon, E. (2004). Visual and auditory temporal processing and early reading development. *Dyslexia, 10*(3), 234-252.

Jaffe-Dax, S., Kimel, E., & Ahissar, M. (2018). Shorter cortical adaptation in dyslexia is broadly distributed in the superior temporal cortex and includes primary auditory cortex. *eLife, 7*, e30018. https://doi.org/10.7554/eLife.30018.001

Keetels, M., Bonte, M., & Vroomen, J. (2018). A selective deficit in phonetic recalibration by text in developmental dyslexia. *Frontiers in Psychology, 9*, 710. https://doi.org/10.3389/fpsyg.2018.00710

Keetels, M., & Vroomen, J. (2007). No effect of auditory-visual spatial disparity on temporal recalibration. *Experimental Brain Research, 182*(4), 559-565.

Kotz, S. A., & Schwartze, M. (2010). Cortical speech processing unplugged: A timely subcortico-cortical framework. *Trends in Cognitive Sciences, 14*(9), 392-399.

Laasonen, M., Service, E., & Virsu, V. (2002). Crossmodal temporal order and processing acuity in developmentally dyslexic young adults. *Brain and Language, 80*(3), 340-354.

Lewkowicz, D. J. (1992). The development of temporally-based intersensory perception in human infants. In F. Macar, V. Pouthas & W. J. Friedman (Eds.), *Time, Action, and Cognition: Towards Bridging the Gap* (Vol. 66, pp. 33-43). Springer, Dordrecht.

Lewkowicz, D. J. (1994). Development of intersensory perception in human infants. In D. J. Lewkowicz & R. Lickliter (Eds.), *The Development of Intersensory Perception: Comparative Perspectives* (pp. 165-203). Psychology Press.

Lewkowicz, D. J. (1996). Perception of auditory-visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance, 22*(5), 1094-1106.

Liu, S., Wang, L. C., & Liu, D. (2019). Auditory, visual, and cross-modal temporal processing skills among Chinese children with developmental dyslexia. *Journal of Learning Disabilities, 52*(6), 431-441.

Meredith, M. A., Nemitz, J. W., & Stein, B. E. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *Journal of Neuroscience, 7*(10), 3215-3229.

Mittag, M., Thesleff, P., Laasonen, M., & Kujala, T. (2013). The neurophysiological basis of the integration of written and heard syllables in dyslexic adults. *Clinical Neurophysiology, 124*(2), 315-326.

Mossbridge, J., Zweig, J., Grabowecky, M., & Suzuki, S. (2017). An association between auditory-visual synchrony processing and reading comprehension: Behavioral and electrophysiological evidence. *Journal of Cognitive Neuroscience, 29*(3), 435-447.

Navarra, J., Hartcher-O' Brien, J., Piazza, E., & Spence, C. (2009). Adaptation to audiovisual asynchrony modulates the speeded detection of sound. *Proceedings of the National Academy of Sciences, 106*(23), 9169-9173.

Navarra, J., Soto-Faraco, S., & Spence, C. (2007). Adaptation to audiotactile asynchrony. *Neuroscience Letters, 413*(1), 72-76.

Navarra, J., Vatakis, A., Zampini, M., Soto-Faraco, S., Humphreys, W., & Spence, C. (2005). Exposure to asynchronous audiovisual speech extends the temporal window for audiovisual integration. *Cognitive Brain Research, 25*(2), 499-507.

Noel, J. P., De Niear, M. A., Stevenson, R., Alais, D., & Wallace, M. T. (2017). Atypical rapid audio-visual temporal recalibration in autism spectrum disorders. *Autism Research, 10*(1), 121-129.

Noel, J. P., De Niear, M. A., van der Burg, E., & Wallace, M. T. (2016). Audiovisual simultaneity judgment and rapid recalibration throughout the lifespan. *PloS One, 11*(8), e0161698. https://doi.org/10.1371/journal.pone.0161698

Noesselt, T., Rieger, J. W., Schoenfeld, M. A., Kanowski, M., Hinrichs, H., Heinze, H. J., & Driver, J. (2007). Audiovisual temporal correspondence modulates human multisensory superior temporal sulcus plus primary sensory cortices. *Journal of Neuroscience, 27*(42), 11431-11441.

O' Connor, I. M., & Klein, P. D. (2004). Exploration of strategies for facilitating the reading comprehension of high-functioning students with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 34*(2), 115-127.

Ozernov-Palchik, O., Beach, S. D., Brown, M., Centanni, T. M., Gaab, N., Kuperberg, G., Perrachione, T. K., & Gabrieli, J. D. E. (2021). Speech-specific perceptual adaptation deficits in children and adults with dyslexia. *Journal of Experimental Psychology: General*. Advance online publication. https://doi.org/10.1037/xge0001145

Pammer, K., & Vidyasagar, T. R. (2005). Integration of the visual and auditory networks in dyslexia: A theoretical perspective. *Journal of Research in Reading, 28*(3), 320–331.

Park, H., & Kayser, C. (2019). Shared neural underpinnings of multisensory integration and trial-by-trial perceptual recalibration in humans. *eLife, 8*, e47001. https://doi.org/10.7554/eLife.47001.001

Patti, P. J., & Lupinetti, L. (1993). Brief report: Implications of hyperlexia in an autistic savant. *Journal of Autism and Developmental Disorders, 23*(2), 397–405.

Pellicano, E., & Burr, D. (2012). When the world becomes 'too real': A Bayesian explanation of autistic perception. *Trends in Cognitive Sciences, 16*(10), 504–510.

Perrachione, T. K., Del Tufo, S. N., Winter, R., Murtagh, J., Cyr, A., Chang, P., ···Gabrieli, J. D. (2016). Dysfunction of rapid neural adaptation in dyslexia. *Neuron, 92*(6), 1383–1397.

Peter, B., McCollum, H., Daliri, A., & Panagiotides, H. (2019). Auditory gating in adults with dyslexia: An ERP account of diminished rapid neural adaptation. *Clinical Neurophysiology, 130*(11), 2182–2192.

Powers, A. R., Hevey, M. A., & Wallace, M. T. (2012). Neural correlates of multisensory perceptual learning. *Journal of Neuroscience, 32*(18), 6263–6274.

Powers, A. R., Hillock, A. R., & Wallace, M. T. (2009). Perceptual training narrows the temporal window of multisensory binding. *Journal of Neuroscience, 29*(39), 12265–12274.

Rüsseler, J., Ye, Z., Gerth, I., Szycik, G. R., & Münte, T. F. (2018). Audio-visual speech perception in adult readers with dyslexia: An fMRI study. *Brain Imaging and Behavior, 12*(2), 357–368.

Sato, Y., & Aihara, K. (2011). A Bayesian model of sensory adaptation. *PloS One, 6*(4), e19377. https://doi.org/10.1371/journal.pone.0019377

Simon, D. M., Nidiffer, A. R., & Wallace, M. T. (2018). Single trial plasticity in evidence accumulation underlies rapid recalibration to asynchronous audiovisual speech. *Scientific Reports, 8*(1), 12345. https://doi.org/10.1038/s41598-018-30414-9

Simon, D. M., Noel, J. P., & Wallace, M. T. (2017). Event related potentials index rapid recalibration to audiovisual temporal asynchrony. *Frontiers in Integrative Neuroscience, 11*, 8. https://doi.org/10.3389/fnint.2017.00008

Stevenson, R. A., Fister, J. K., Barnett, Z. P., Nidiffer, A. R., & Wallace, M. T. (2012). Interactions between the spatial and temporal stimulus factors that influence multisensory integration in human performance. *Experimental Brain Research, 219*(1), 121–137.

Stevenson, R. A., Segers, M., Ferber, S., Barense, M. D., Camarata, S., & Wallace, M. T. (2016). Keeping time in the brain: Autism spectrum disorder and audiovisual temporal processing. *Autism Research, 9*(7), 720–738.

Stevenson, R. A., & Wallace, M. T. (2013). Multisensory temporal integration: Task and stimulus dependencies. *Experimental Brain Research, 227*(2), 249–261.

Theves, S., Chan, J. S., Naumer, M. J., & Kaiser, J. (2020). Improving audio-visual temporal perception through training enhances beta-band activity. *NeuroImage, 206*, 116312. https://doi.org/10.1016/j.neuroimage.2019.116312

Turi, M., Karaminis, T., Pellicano, E., & Burr, D. (2016). No rapid audiovisual recalibration in adults on the autism spectrum. *Scientific Reports, 6*, 21756. https://doi.org/10.1038/srep21756

Ullas, S., Hausfeld, L., Cutler, A., Eisner, F., & Formisano, E. (2020). Neural correlates of phonetic adaptation as induced by lexical and audiovisual context. *Journal of Cognitive Neuroscience, 32*(11), 2145–2158.

Van der Burg, E., Alais, D., & Cass, J. (2013). Rapid recalibration to audiovisual asynchrony. *Journal of Neuroscience, 33*(38), 14633–14637.

Van der Burg, E., Alais, D., & Cass, J. (2015). Audiovisual temporal recalibration occurs independently at two different time scales. *Scientific Reports, 5*, 14526. https://doi.org/10.1038/srep14526

Van der Burg, E., & Goodbourn, P. T. (2015). Rapid, generalized adaptation to asynchronous audiovisual speech. *Proceedings of the Royal Society B: Biological Sciences, 282*(1804), 20143083. https://doi.org/10.1098/rspb.2014.3083

Van Wassenhove, V., Grant, K. W., & Poeppel, D. (2007). Temporal window of integration in auditory-visual speech perception. *Neuropsychologia, 45*(3), 598–607.

Vidyasagar, T. R., & Pammer, K. (2010). Dyslexia: A deficit in visuo-spatial attention, not in phonological processing. *Trends in Cognitive Sciences, 14*(2), 57–63.

Virsu, V., Lahti-Nuuttila, P., & Laasonen, M. (2003). Crossmodal temporal processing acuity impairment aggravates with age in developmental dyslexia. *Neuroscience Letters, 336*(3), 151–154.

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, and Psychophysics, 72*(4), 871–884.

Wallace, M. T., & Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia, 64*, 105-123.

Woynaroski, T. G., Kwakye, L. D., Foss-Feig, J. H., Stevenson, R. A., Stone, W. L., & Wallace, M. T. (2013). Multisensory speech perception in children with autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*(12), 2891-2902.

Yu, L., Stein, B. E., & Rowland, B. A. (2009). Adult plasticity in multisensory neurons: Short-term experience-dependent changes in the superior colliculus. *Journal of Neuroscience, 29*(50), 15910-15922.

Zaidel, A., Goin-Kochel, R. P., & Angelaki, D. E. (2015). Self-motion perception in autism is compromised by visual noise but integrated optimally across multiple senses. *Proceedings of the National Academy of Sciences, 112*(20), 6461-6466.

Zhou, H. Y., Cheung, E. F., & Chan, R. C. (2020). Audiovisual temporal integration: Cognitive processing, neural mechanisms, developmental trajectory and potential interventions. *Neuropsychologia, 140*, 107396. https://doi.org/10.1016/j.neuropsychologia.2020.107396

Zhou, H. Y., Shi, L. J., Yang, H. X., Cheung, E. F., & Chan, R. C. (2020). Audiovisual temporal integration and rapid temporal recalibration in adolescents and adults: Age-related changes and its correlation with autistic traits. *Autism Research, 13*(4), 615-626.

Note: Figure translations are in progress. See original paper for figures.