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Temporal processing in autism spectrum disorder and developmental dyslexia: A systematic review and meta-analysis

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Résumé

Les individus ayant un trouble du spectre de l'autisme (TSA) ou une dyslexie développementale (DD) semblent avoir des difficultés de traitement temporel. Ces difficultés peuvent avoir un impact sur des processus de haut-niveau, comme la communication, les compétences sociales, la lecture et l'écriture. La présente méta-analyse a examiné deux tests de traitement temporel afin de remplir les objectifs suivants: 1) déterminer si les difficultés de traitement temporel sont un trait commun au TSA et à la DD, et ce pour le traitement multisensoriel et unisensoriel, pour différentes modalités et types de stimuli, 2) d'évaluer la relation entre la sévérité clinique et le traitement temporel, et 3) d'examiner l'effet de l'âge sur le traitement temporel. Les résultats ont montré un déficit de traitement temporel dans le TSA et la DD, caractérisé de déficits multisensoriels chez ces deux populations, et de déficits unisensoriels auditifs, tactiles et visuels pour la DD. De plus, notre analyse de la sévérité clinique indique qu'un meilleur traitement temporel en DD est associé à de meilleures compétences en lecture. Enfin, les déficits de traitement temporel ne varient pas avec l'âge des individus TSA et DD, ils sont donc présents tout au long du développement et de la vie adulte. En conclusion, les résultats de la méta-analyse montrent que les difficultés de traitement temporel font partie du cadre clinique du TSA et de la DD et permettent d'émettre des recommandations pour de futures recherches et interventions.

Mots clé: Trouble du spectre de l'autisme; Dyslexie développementale; Intégration sensorielle; Traitement temporel; Fenêtre d'intégration temporelle; Méta-analyse

Abstract

Individuals with autism spectrum disorder (ASD) or developmental dyslexia (DD) are commonly reported to have deficits in temporal processing. These deficits can impact higher-order processes, such as social communication, reading and writing. In this thesis, quantitative meta-analyses are used to examine two temporal processing tasks, with the following objectives: 1) determine whether temporal processing deficits are a consistent feature of ASD and DD across specific task contexts such as multisensory and unisensory processing, modality and stimulus type, 2) investigate the relationship between symptom severity and temporal processing, and 3) examine the effect of age on temporal processing deficits. The results provide strong evidence for impaired temporal processing in both ASD and DD, as measured by judgments of temporal order and simultaneity. Multisensory temporal processing was impaired for both ASD and DD, and unisensory auditory, tactile and visual processing was impaired in DD. Greater reading and spelling skills in DD were associated with greater temporal precision. Temporal deficits did not show changes with age in either disorder. In addition to more clearly defining temporal impairments in ASD and DD, the results highlight common and distinct patterns of temporal processing between these disorders. Deficits are discussed in relation to existing theoretical models, and recommendations are made for future research and interventions.

Keywords: Autism spectrum disorder, Developmental dyslexia, Sensory integration, Temporal processing, Temporal binding window, Meta-analysis

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List of abbreviations

ADOS	Autism Diagnostic Observation Schedule
APA	American Psychiatric Association
ASD	Autism Spectrum Disorder
DD	Developmental Dyslexia
IQ	Intellectual Quotient
SJ	Simultaneity Judgment
SRS	Social Responsiveness Scale
TD	Typical Development
TOJ	Temporal Order Judgment

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Introduction

Autism spectrum disorder (ASD) and developmental dyslexia (DD) are neurodevelopmental disorders associated with sensory processing deficits. Individuals with ASD or DD show deficits in processing stimuli that are close together in time, as well as temporally integrating sensory information from different sensory modalities (Wallace & Stevenson, 2014). However, it is unclear whether atypical temporal processing is a consistent feature in both disorders, or whether deficits are linked with symptom severity and development. This thesis presents a quantitative behavioral meta-analysis of systematically reviewed research on temporal processing in ASD and DD. The specific aims of this work were to determine if temporal sensory impairments are consistent features of ASD and DD, and to evaluate if temporal processing is related to development and clinical symptom severity. The ultimate goal of this research is to compare both disorders to gain a clearer understanding of the common and unique aspects of temporal processing. By achieving this, the goal is for future studies to arrive at a conceptualization of how temporal processing may explain or modulate the specific clinical severity profiles in ASD and DD.

Overview of ASD

The diagnosis of ASD as we know it today has evolved considerably since its first descriptions in the 1940s. Two researchers shared their own observations of what is now considered to fall within the broad spectrum of autism. On the one hand, Hans Asperger (1944) described individuals who struggled with social relationships, had odd ways of learning and communicating, and showed narrow interests. These individuals would be known as having Asperger Syndrome in the years to come. On the other hand, Leo Kanner (1943) gave an account of children that had low cognitive and linguistic abilities, but also showed the characteristics described by Asperger (social impairments, odd communication and restricted interests). Associated with psychosis and schizophrenia, autism was thought of as a precursor to adult psychiatric disorders, such as schizophrenia. It was in the 1970s, by means of clinical observations, that clinicians realized ASD was not a form of childhood mental disorder, and noted that it was often associated with other medical conditions such as epilepsy (Kolvin, 1971; Rutter, 1972). ASD was increasingly seen as a neurological condition, influenced by genetics, and is now an accepted neurodevelopmental disorder that is recognizable early in life (Wolf, 2004).

ASD is currently understood as a heterogeneous neurodevelopmental disorder with a complex genetic component, present in 1 out of 59 individuals in the population (Baio, 2014; Devlin and Scherer, 2012). Other disorders are comorbid with ASD, as 70% of individuals with ASD have a second diagnosis, the most common ones being anxiety and attention deficit and hyperactivity disorder (ADHD) (Simonoff et al., 2008). Since 2013, both types of described individuals (Asperger syndrome and autistic) are included under the same diagnostic umbrella of ASD (American Psychiatric Association [APA], 2013). ASD is described as having two principal domains of impairments: 1) deficits in the social-communication domain, 2) and restricted and repetitive behaviors (APA, 2013). Also in 2013, atypical sensory processing was added as a symptom to the diagnostic criteria. Included under the restricted and repetitive behaviors domain, atypical sensory processing is generally noted by hyperreactivity or hyporeactivity to sensory stimuli. Its inclusion in the diagnostic profile has spurred research interest as researchers seek to describe and understand sensory processing and its relation to other core aspects of ASD. In particular, multisensory integration has been proposed as an area of impairment that could play a role in social and communicative deficits in ASD (Wallace and Stevenson, 2014).

Overview of DD

In 1877, the German ophthalmologist Rudolf Berlin coined the term "dyslexia", after studying patients who had difficulty with written words, without any clear visual impairments (Wagner, 1973). Subsequently, Pringle Morgan studied patients with "congenital word blindness", a term he coined because of the pronounced disability that was specific to reading and didn't seem to benefit from additional teaching (Morgan, 1896). The boy he studied was intelligent and able to perform a range of academic and daily activities aside from reading and spelling. This famous case study and many more motivated interest for research of this condition, also known as dyslexia, throughout the 20th century (Benton, 1980). In 1920, it was theorized that DD was caused by a deficit in the visual system that changed the perception of letters and words, making them appear backwards to the DD reader. This theory was debated and disproved by following research (Shaywitz & Shaywitz, 2003). Conversely, the hereditary aspect of dyslexia was acknowledged early on and was supported by numerous research and clinical observations in the early 20th century (Zahalkova, Vrzal, & Kloboukova, 1972).

Currently known as a neurodevelopmental disorder, DD is characterized by severe difficulties decoding written words with a preserved oral language comprehension (Lyon, Shaywitz, & Shaywitz, 2003). The major impairments in DD lie in phonological awareness (i.e. manipulating speech sounds) and lexical access (i.e. translating visual symbols to speech sounds) (Logan, Schatschneider, & Wagner, 2011). According to the diagnostic criteria (specific learning disorder), these difficulties arise despite adequate formal education opportunities and are not due to other conditions, such as intellectual disability (APA, 2013).

Of all neurodevelopmental disorders, such as ASD and ADHD, DD is the most common in children, with prevalence rates at around 7% (Peterson and Pennington, 2012). DD is also very heterogeneous, and part of this heterogeneity arises from associations with different comorbid disorders, such as ADHD, dyscalculia and specific language impairments (Pennington, 2006; Peterson and Pennington, 2012). There are many sub-phenotypes present within the DD diagnosis, the most common being surface dyslexia and phonological dyslexia (Landerl et al., 2009; Stanovich et al., 1997). Whereas surface dyslexia shows intact sound-to-letter mapping but poor visual recognition of familiar words, phonological dyslexia involves difficulties in reading unknown words due to poor sound-to-letter mapping (Castles and Coltheart, 1993).

Although individuals with DD have intact visual and auditory input, they show various deficits in sensory processing, including temporal processing. As such, temporal processing skills in DD have been investigated as a possible fundamental factor in the development of phonological processing deficits and the manifestation of reading and writing delays (Francisco et al., 2017b; Vandermosten et al., 2011).

Temporal processing and related tasks

The human body's sensory organs receive auditory, gustatory, olfactory, tactile, visual, and proprioceptive information. A unified percept of the environment is subsequently created by the nervous system, by organizing, combining and interpreting these sensory signals (Stein & Meredith, 1993). Temporal processing is a crucial aspect of this sensory processing, in order to resolve and integrate sensory events in the moment and over time.

Broadly speaking, establishing temporal relations for stimuli in our environment is a foundation for understanding the world. For example, auditory temporal processing enables us to discern units of sounds in speech perception, which in turn facilitates higher-order communicative skills like reading and writing (Mauk & Buonomano, 2004). Temporal processing is also essential for integrating sensory information across different modalities. For instance, everyday conversation involves the rapid integration of auditory and visual information to create a holistic and dynamic percept. Failure to temporally integrate these sensory cues can lead to deficits in speech perception (Stevenson et al., 2014; Stevenson et al., 2017). Temporal processing will be approached here in terms of tasks involved in discerning relative timing between sensory events, which has been shown to be atypical in ASD and DD (Wallace & Stevenson, 2014). To note, the study of temporal processing in ASD and DD is not limited to the relative timing of sensory events. Other tasks, such as beat-based timing tasks, have sought to understand temporal processing in both populations (e.g.: Goswami et al., 2013; Jamey et al., 2019).

The temporal processing of stimulus events can be measured in terms of the acuity of discerning individual events within a sensory modality (unisensory processing), as well as the integration (or binding) of events across senses (multisensory processing). Generally, stimuli that are close together in time will be associated to the same event. The temporal binding window (TBW) is used to define this period of time within which two stimuli from different senses are most likely to be perceptually bound, even if they are not perfectly synchronous (Wallace and Stevenson, 2014). Conversely, if two stimuli are asynchronous to the extent that the difference in onset time exceeds the TBW, those stimuli are likely to be perceived as coming from different events, i.e., will not be bound. The TBW varies across individuals, and the width of one's TBW reflects temporal acuity in the individual senses. Moreover, multisensory TBW size can reflect underlying unisensory temporal acuity, as demonstrated in a study in which visual temporal processing training led to a reduced TBW in an audio-visual processing task (Stevenson et al., 2013). Different stimuli can also alter the size of the measured TBW, as in the case of speech stimuli which typically yield larger windows (Stevenson et al., 2012). Larger TBWs in individuals or clinical populations can indicate deficits in temporal integration, arising from imprecise temporal processing of sensory stimuli (Stevenson et al., 2014). Over the course of typical development, children gradually gain temporal acuity while adults become less accurate with old age, and accordingly during childhood years, the TBW narrows during childhood development and then progressively widens through the subsequent decades of life (Bedard and Barnett-Cowan, 2016; Di Lollo et al., 1982; Hillock et al., 2011; Lewkowicz, 1996; Lewkowicz and Flom, 2014; Setti et al., 2011).

Two tasks are typically used to measure the accuracy of temporal binding, which involve relative timing judgments. These tasks are the simultaneity judgement (SJ) task, in which participants decide whether two stimuli were presented simultaneously or asynchronously (e.g., Falter et al., 2012), and the temporal order judgement (TOJ) task, in which participants judge which of two stimuli was presented first (e.g., Chung et al., 2008). In both tasks, the stimulus onset asynchrony (SOA) is varied, changing the difficulty of the timing judgment across trials (see fig. 1a). Having poor temporal acuity is reflected in longer SOAs required to accurately judge the relative timing of stimuli. The SOA is one of the ways to conceptualize the temporal space between stimuli and it describes the time between their onset. Another common way to conceptualize this temporal gap is the interstimulus interval (IS), which is the distance between the offset of the first stimuli and the onset of the second one. In other words, adding the duration of the first stimulus to the ISI defines the SOA. Both the SOA and the ISI are used to describe stimuli in the SJ and TOJ literature, depending on the researchers' preference (see figure 1a).

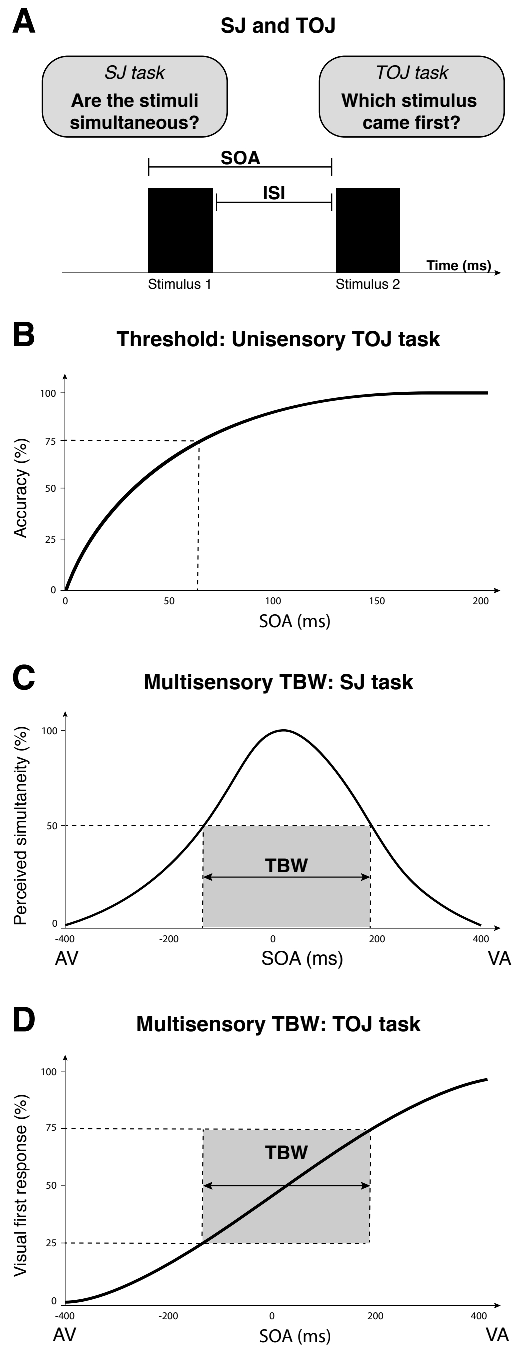

Fig. 1. Diagrams of stimuli, judgments and common performance measures for SJ and TOJ tasks. (a) SJ and TOJ tasks both involve two stimuli that are separated by varying time intervals (SOA or ISI) or may be simultaneous. (b) TOJ performance (unisensory or multisensory) is usually calculated as a threshold (in ms) corresponding to a pre-chosen level of accuracy. (c) SJ tasks often serve to calculate the multisensory TBW. (d) Multisensory TBW can also be measured with TOJ tasks.

The SJ and TOJ tasks are typically used in the auditory, visual and tactile modalities. In unisensory TOJ and SJ tasks, temporal judgments are made upon stimuli within the same modality. Traditionally, the two stimuli differ either in spatial location or physical attribute. For example, a TOJ task will require participants to order two sounds that are heard in two different ears (spatial location) or that have a different frequency (attribute). Unisensory tasks will typically measure a threshold (see figure 1d) at which performance reaches a predetermined level (e.g., 75% accuracy). These can be estimated using a fixed set of SOAs or ISI, for which a predetermined number of trials are presented for each chosen SOA or ISI (e.g., Ben-Artzi et al., 2005). An alternative method is the adaptive staircase procedure, which progressively changes the distance between stimuli according to participants' response accuracy (Rose et al., 1970).

In contrast, the multisensory versions of these tasks assess binding or temporal discrimination between modalities (Laasonen et al., 2012; Noel et al., 2018a). With multisensory TOJ and SJ, a probability curve for performance as a function of SOA can be calculated, from which a performance threshold or the temporal binding window (TBW) can be estimated.

Sensory temporal processing in ASD

Clinical reports of atypical sensory reactivity (hyper- and hyporeactivity) to sensory stimuli point to disrupted sensory processing in ASD (Baum, Stevenson, & Wallace, 2015; Leekam, Nieto, Libby, Wing, & Gould, 2007). The presence of atypical sensory processing in ASD has also been supported by studies showing both enhanced and reduced abilities (Wallace and Stevenson, 2014). For example, in the auditory modality, pitch discrimination may be enhanced (Bonnel et al., 2003), but performance in more complex tasks involving speech can be atypical or impaired (see O'Connor, 2012). Temporal processing might be one of the possible explanations for atypical processing of sensory information.

Temporal processing theories

Existing theories of sensory processing in ASD state that low-level and local elements are processed more efficiently or readily compared to higher-level more complex stimuli (Happé and Frith, 2006; Mottron et al., 2006). Specifically, the Enhanced Perceptual Functioning (EPF) model, although not founded on temporal processing research, makes the claim that ASD is associated with superior performance in low-level perceptual operations (Mottron et al. 2006). The Weak Central Coherence Theory proposes that perceptual atypicalities in ASD result from poor integration of local features into holistic percepts at the global level, explaining poor global processing of auditory and visual information (Happé and Frith, 2006). According to both theories, unisensory processing should show no impairment, or may even show an advantage for ASD compared to TD according to EPF. Conversely, multisensory processing could be impaired, as this involves operations across multiple modalities and involves the integration of multiple paths of sensory information. Additionally, Brock's (2002) binding theory is applied to ASD to explain sensory alterations, particularly with multisensory integration relating to the TBW (Thye, Bednarz, Herringshaw, Sartin, & Kana, 2018). It states that temporal information is necessary to properly bind associated stimuli, such that sensory stimuli that are close in time are more likely to be integrated together. This theory makes the prediction of poor multisensory temporal processing in ASD. It is still unclear to what extent unisensory processing compares to multisensory processing in TOJ and SJ tasks.

Evidence for atypical temporal processing

The evidence for unisensory temporal processing in ASD is mixed, as some results show increased temporal acuity and others point to diminished acuity. For example, adults with ASD were better able to tell the difference between simultaneous and nonsimultaneous visual cues in SJ tasks compared to typically developing adults (Falter et al., 2012; Falter et al., 2013), whereas children with ASD were impaired in making auditory TOJ but not visual TOJ (Kwakye et al., 2011). In contrast, multisensory temporal processing shows more consistent deficits, as measured by the TBW (Foss-Feig et al., 2010; Kwakye et al., 2011; Noel et al., 2018b; Zhou et al., 2018). Most studies have found larger TBWs for participants in the ASD group, meaning they perceive multisensory information as being simultaneous even when they are asynchronous by a longer period of time. On the other hand, some studies have reported no differences in TBW size for ASD (e.g., Turi et al., 2016), or only found increases when using speech stimuli (e.g., Stevenson et al., 2014). It remains unknown whether temporal processing is impaired in ASD only in specific contexts, such as task modality and stimuli type, or whether it is a more general impairment that persists across contexts.

Temporal processing and multisensory integration are essential to form correct perceptual representations, which serve as a foundation for higher cognitive functions (Baum et al., 2015). Failing to acquire these perceptual representations might lead to higher order deficits such as social and communicative deficits. Specifically, Stevenson et al. (2017) found a relationship between multisensory temporal processing and speech perception in ASD, in which a narrower TBW in a TOJ task was associated with more accurate speech-in-noise perception. Alternatively, Smith et al. (2017) showed that individuals with ASD had a narrower TBW, and within ASD a narrower TBW was associated with greater symptom severity. These studies provide evidence that temporal processing in ASD is associated with symptomatology, but the direction of this association remains unclear.

No studies have directly investigated the relationship between temporal processing and age in ASD. That being said, evidence from non-temporal multisensory integration studies points to a pattern of development in ASD that parallels neurotypical development. For example, young children with ASD do not perceive the McGurk illusion, an audiovisual integration task, whereas older children and adults with ASD usually do, which is indicative of successful multisensory integration (Foxe et al., 2013; Taylor, Isaac, and Milne, 2010). Furthermore, recent reviews of audiovisual integration in ASD generally find that group differences between ASD and TD individuals lessens over the course of development (Beker et al., 2018; Feldman et al., 2018).

Sensory temporal processing in DD

It is generally understood that DD is characterised by impairments in phonological processing, comprising poor phonological awareness, poor verbal short-term memory, and slow lexical retrieval (Vellutino et al., 2004; Ramus and Szenkovits, 2008). There is debate over the potential underlying mechanisms that give rise to these phonological deficits in dyslexia, as researchers wonder what mechanisms may be at cause (Vidyasagar and Pammer, 2009; Stein, 2018). As such, temporal processing skills in DD have been investigated as a possible fundamental factor in the development of phonological processing deficits and the manifestation of reading and writing delays (e.g., Francisco et al., 2017b; Vandermosten et al., 2011).

Temporal processing theories

A prominent theory in DD is the rapid auditory processing (RAP) deficit, which posits that auditory temporal impairments cause deficits in both the perception and production of speech sounds (Tallal, 1980). The RAP deficit entails problems processing brief auditory cues, which can lead to inaccurate perception of phonemic contrasts, which could in turn alter basic reading and writing skills (Farmer and Klein, 1995). Atypical visual temporal processing in DD also plays a potential role in explaining this disorder, according to the magnocellular theory. The theory supports the idea that the development and functioning of the magnocellular cells, responsible for the rapid processing of visual information in the brain, are both impaired in DD (Stein and Walsh, 1997). According to Stein (2018), visual timing deficits in DD are partly responsible for the deficits seen in reading and writing but are among many determining factors of literacy. Accordingly, many theories have been formulated around one modality or one cause (Goswami, 2011; Hari & Renvall, 2001), and others that account for deficits in two modalities or for deficits in different processes (Fostick et al., 2018; Wolf and Bowers, 1999).

Evidence for atypical temporal processing

Individuals with DD show deficits across a broad range of temporal processing tasks, in auditory, visual and tactile processing (Hämäläinen et al. 2013; Laasonen et al., 2012; Pammer, 2014). In terms of unisensory temporal processing in TOJ and SJ tasks, what is shown is that individuals with DD need longer SOAs to judge the order of two consecutive auditory or visual stimuli, compared to control participants (Ben-Artzi et al., 2005; Hairston et al., 2005). Both auditory and visual unisensory temporal processing has been shown to correlate with phonological awareness and reading measures (Fostick et al., 2018; Kinsbourne et al., 1991).

In terms of multisensory temporal processing, deficits in temporal audiovisual integration have been shown with SJ and TOJ tasks and have been hypothesized to play a role in reading difficulties in DD (Hahn et al., 2014). Current data point toward a larger TBW for both audiovisual speech and non-speech stimuli in DD (Laasonen et al., 2002b; Virsu et al., 2003). Moreover, multisensory temporal acuity, as defined by performance on the TOJ and SJ tasks, is correlated with phonological awareness (Laasonen et al., 2002b), which is an essential ability for developing adequate reading and writing skills (Melby-Lervåg et al., 2012). Notably, Francisco et al. (2017b) reported that audiovisual temporal sensitivity was a unique predictor of reading errors in DD participants using a SJ task. Both unisensory and multisensory evidence points to a link between temporal processing and reading outcomes, although the strength of this association remains unknown.

Temporal processing in DD exhibits a developmental pattern that is comparable to typical development. Specifically, temporal acuity is positively correlated with age during childhood (Lorusso et al., 2014; Wang and Yang, 2018) and negatively correlated with adult aging (Hairston et al., 2005; Virsu et al., 2003). Nevertheless, it is still unknown whether temporal processing in DD shows equivalent impairment between the visual and auditory modalities, nor whether multisensory processing is impaired to the same extent as in unisensory processing. The true nature of phonological deficits in DD is still unknown, and much debate remains on the mechanisms behind reading and writing deficits seen in this disorder.

Study objectives

Reports of poor temporal acuity and atypical TBW sizes in ASD and DD suggest that both disorders may have impaired unisensory and multisensory temporal processing. However, these findings are based on individual studies which typically have a small sample size. In order to have a more comprehensive understanding of temporal perceptual abilities or impairments in ASD and DD respectively, a systematic review and quantitative meta-analysis was conducted. Unlike traditional literature reviews, meta-analyses offer the advantage of providing a systematic statistical analysis of previous data (Lipsey & Wilson, 2001). Additionally, the objective of this work was to bring together two neurodevelopmental disorders in order to better understand the role of temporal processing in neurodevelopmental disorders. Temporal perception is affected in a number of clinical populations and is thought to cascade into higher-order deficits specific to each population (Wallace and Stevenson, 2014; Zhou et al., 2018). However, it is currently unknown how impairments in temporal processing lead to different patterns of performance in relation to sensory modality, complexity of stimuli (speech or nonspeech), and binding across modalities in different disorders. Two of the developmental disorders in which temporal perception has been most studied are ASD and DD, which we aim to compare to gain a clearer understanding of the common and unique aspects of temporal processing. By achieving this, the goal is for future studies to arrive at a conceptualization of how temporal processing may explain or modulate the specific clinical severity profiles in ASD and DD.

The ultimate mission of this research is to better refine these clinical phenotypes and to set a theoretical groundwork for future interventions in ASD and DD that could potentially ameliorate atypical temporal processing and lead to improved outcomes in core symptoms (Bidelman, 2016; Stevenson, Wilson, Powers, & Wallace, 2013).

Aims and hypotheses

The first aim was to quantitatively review the evidence for temporal processing in ASD and DD and determine if temporal processing deficits are cardinal features for both disorders, and whether the deficits vary across different task contexts such as processing type (multisensory or unisensory), modality, or stimulus type (speech or nonspeech). It was expected that temporal processing would be shown to be impaired in ASD (Kwakye et al., 2011; Noel et al., 2018b) and DD (Laasonen et al., 2001; Hairston et al., 2005) in terms of both poorer unisensory and multisensory temporal acuity (larger TBWs). Speech stimuli in ASD were expected to be associated with greater deficits compared to nonspeech stimuli, because speech stimuli are more complex to process (Beker et al., 2018). Speech stimuli were not investigated in DD because of methodological limitations in the studies that assessed speech order judgments in this population (see 2.1). In DD, the visual and auditory modalities were expected to both yield impairments in temporal processing.

The second aim was to investigate the relation between temporal processing and symptom severity in ASD and DD. It was expected that temporal processing would be associated with symptom severity for both disorders. Specifically, poor temporal acuity and larger TBWs would be related to greater symptom severity in ASD (Brandwein et al., 2015; Stevenson et al., 2017) and DD (Francisco et al., 2017b).

The third aim was to examine the relation between temporal processing and age. It was expected that measures of temporal acuity would follow a developmental trajectory similar to what is seen in typical development, such that processing improves during childhood and degrades with aging (Hillock et al., 2011; Bedard and Barnett-Cowan, 2015).

Confirmation of submission

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Unisensory and multisensory temporal processing in autism and dyslexia: A systematic review and meta-analysis

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Abstract

This study presents a comprehensive systematic review and meta-analysis of temporal processing in autism spectrum disorder (ASD) and developmental dyslexia (DD), two neurodevelopmental disorders in which temporal processing deficits have been highly researched. The results provide strong evidence for impairments in temporal processing in both ASD (g = 0.48) and DD (g = 0.82), as measured by judgments of temporal order and simultaneity. In individual analyses, multisensory temporal processing was impaired for both ASD and DD, and unisensory auditory, visual and tactile processing were all impaired in DD. In ASD, speech stimuli showed moderate impairment effect sizes, whereas nonspeech stimuli showed small effects. Greater reading and spelling skills in DD were associated with greater temporal precision. Temporal deficits did not show changes with age in either disorder. In addition to more clearly defining temporal impairments in ASD and DD, the results highlight common and distinct patterns of temporal processing between these disorders. Deficits are discussed in relation to existing theoretical models, and recommendations are made for future research.

Keywords: Autism spectrum disorder, Developmental dyslexia, Sensory integration, Temporal processing, Temporal binding window, Meta-analysis

1. Introduction

Establishing temporal relations for stimuli in our environment is a foundation for understanding the world around us. For example, auditory temporal processing provides the means to discern units of sounds in speech perception, which in turn facilitates higher-order communicative skills like reading and writing (Mauk and Buonomano, 2004). Temporal processing is also essential for integrating sensory information across different modalities. For instance, everyday conversation involves the rapid integration of auditory and visual information to create a holistic and dynamic percept. Failure to temporally integrate these sensory cues can lead to deficits in speech perception (Stevenson et al., 2014; Stevenson et al., 2018). Temporal processing, and specifically discerning the relative timing between sensory events, has been shown to be atypical in neurodevelopmental disorders (Wallace and Stevenson, 2014). Autism spectrum disorder (ASD) and developmental dyslexia (DD) are two disorders in which temporal processing deficits have been highly studied. In addition, sensory processing atypicalities have been proposed to contribute to core behavioral symptoms in ASD and DD (Mikkelsen, Wodka, Mostofsky, Puts, 2018; Wallace and Stevenson, 2014). By comparing these two neurodevelopmental disorders, which exhibit limited co-occurrence (Brown et al., 2013; Hendren et al., 2018; Mattila et al., 2010; Peterson & Pennington, 2012; Snowling, 2012), it is hoped that a clearer understanding of the common and unique aspects of temporal perception can be achieved, leading to a clearer understanding of how temporal perception may explain or modulate the specific clinical severity profiles in ASD and DD. It is currently unclear whether atypical temporal processing is a consistent feature in both disorders, and whether deficits are linked with symptom severity and development. This review provides an updated qualitative and quantitative assessment of temporal processing impairments in both ASD and DD, and aims to guide future studies of temporal sensory processing and potential interventions in these populations.

ASD is a heterogeneous disorder characterized by social and communication impairments and restricted, repetitive patterns of behavior (American Psychiatric Association [APA], 2013). Sensory dysfunctions have been recognized as an important aspect of ASD in the fifth edition of the Diagnostic and Statistical Manual (DSM-5; APA, 2013). Sensory atypicalities in ASD can be present in one sensory modality or more, and sometimes include hypo- or hyperreactivity to sensory input (Ausderau et al., 2014; Kern et al., 2006; Leekam et al., 2007). These atypicalities have been reported for modalities such as auditory, tactile, visual, olfactory, taste and proprioception (Ben-Sasson et al., 2009; Kientz and Dunn, 1997). Following the update to DSM-5 diagnostic criteria, a body of research has focused on understanding the nature of these sensory dysfunctions and their relation with other core symptoms (Ben-Sasson et al., 2019). In particular, sensory features are believed to impact social features, with sensory problems leading to social dysfunctions through different mechanisms (Thye et al., 2018). However, temporal processing, its development and its relation to symptom severity are not yet well understood.

DD is a learning disorder characterized by deficits in reading and writing abilities in individuals with normal intelligence, normal educational opportunities and intact sensory abilities (APA, 2013). Individuals with DD have severe difficulties decoding written words, whereas their oral language comprehension is relatively spared (Lyon et al., 2003). DD includes impairments in phonological awareness (i.e., manipulating speech sounds) and lexical access (i.e., translating visual symbols to speech sounds) (Logan et al, 2011). Although individuals with DD have intact low-level visual and auditory input, they show various deficits in sensory processing, and particularly in temporal processing (Hahn et al., 2014; Hämäläinen et al. 2013). Different theories in dyslexia suggest that either or both auditory and visual processing impairments could explain core DD deficits (see Goswami, 2015). However, little is known about the extent of these temporal processing difficulties and their relation with reading and writing abilities.

1.1. Temporal processing in typically developing (TD) individuals

Temporal processing is a key aspect of sensory processing because the timing of sensory information serves as an important cue for resolving and integrating sensory events (Meredith et al., 1987; Meredith and Stein, 1996). Generally, stimuli that are close together in time will be associated to the same event. The temporal processing of stimulus events can be measured in terms of the acuity of discerning individual events within a sensory modality, as well as the integration (or binding) of events across senses. The temporal binding window (TBW) is used to define this period of time within which two stimuli from different senses are most likely to be perceptually bound, even if they are not perfectly synchronous (Wallace and Stevenson, 2014). Conversely, if two stimuli are asynchronous to the extent that the difference in onset time exceeds the TBW, those stimuli are likely to be perceived as coming from different events, i.e., will not be bound. The TBW varies across individuals, and the width of one's TBW will likely change over the course of development (Bedard and Barnett-Cowan, 2016; Hillock et al., 2011). Moreover, multisensory TBW size can reflect underlying unisensory temporal acuity, as demonstrated in a study in which visual temporal order judgement (TOJ) training led to a reduced TBW in an audio-visual TOJ task (Stevenson et al., 2013). Different stimuli can also affect the size of the measured TBW; for example speech stimuli typically yield larger windows (Stevenson et al., 2012). Larger TBWs can indicate deficits in temporal integration, showing imprecise temporal processing of sensory stimuli (Stevenson et al., 2014).

The TBW has shown to be somewhat malleable in response to audiovisual training (Powers et al., 2016; Stevenson et al., 2013; Zerr et al., 2019). Improved timing precision after training is reflected in brain activation changes in posterior temporal cortex, which is known for its involvement in audiovisual synchrony perception along with other regions such as the cerebellum (Powers et al., 2012). Other brain areas identified as important for timing decisions during unisensory timing tasks include the basal ganglia and the insula (Kosillo and Smith, 2010; Love et al., 2018; Miyazaki et al., 2016).

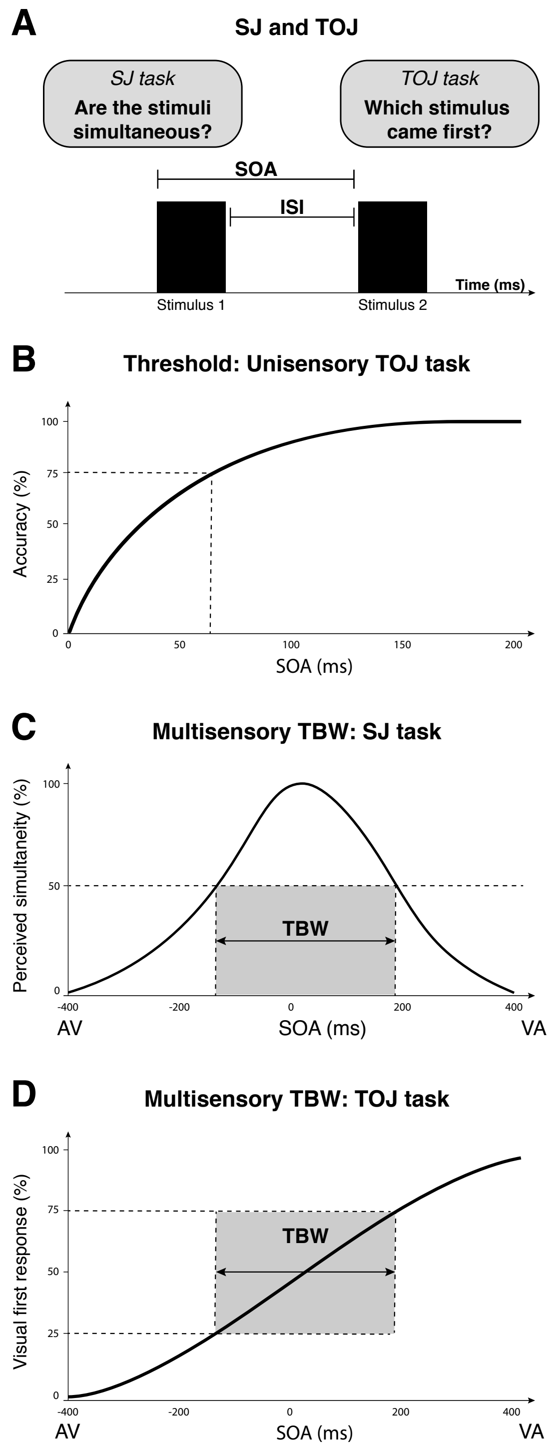

Fig. 1. Diagrams of stimuli, judgments and common performance measures for SJ and TOJ tasks. (a) SJ and TOJ tasks both involve two stimuli that are separated by varying time intervals (SOA or ISI) or may be simultaneous. (b) TOJ performance (unisensory or multisensory) is usually calculated as a threshold (in ms) corresponding to a pre-chosen level of accuracy. (c) SJ tasks often serve to calculate the multisensory TBW. (d) Multisensory TBW can also be measured with TOJ tasks.

1.2. Measuring temporal processing

Two tasks are typically used to measure the accuracy of relative timing judgments. In the simultaneity judgement (SJ) task, participants decide whether two stimuli were presented simultaneously or asynchronously. For example, in Falter et al. (2012), two vertical bars appeared either simultaneously or with different onsets, and remained onscreen. In the TOJ task, participants judge which of two stimuli was presented first. For example, Chung et al. (2008), a circle and a cross was presented on each trial, with varying presentation order. For both these tasks, the level of difficulty can be modified with the timing of stimuli presentation (i.e. smaller time difference between stimulus onsets increases difficulty).

The relative timing between the stimuli can be described in terms of the stimulus onset asynchrony (SOA), which indicates the difference in start time between the two stimuli, or the interstimulus interval (ISI), which indicates the time between the end of the first stimulus and the start of the second. In the present study, SOA will be used to describe relative timing. In both the SJ and TOJ tasks, the SOA is varied, changing the difficulty of the timing judgment across trials (see Fig. 1a). Having poor temporal acuity is reflected in longer SOAs required to accurately judge the relative timing of stimuli.

These two tasks are typically used in the auditory, visual and tactile modalities. In unisensory SJ and TOJ tasks, temporal judgments are made upon stimuli within the same modality, whereas the multisensory versions of these tasks assess binding or temporal discrimination between modalities (Laasonen et al., 2012; Noel et al., 2018a). Unisensory tasks typically are used to measure the threshold at which performance reaches a predetermined level (e.g., 75% accuracy; see Fig. 1b). These thresholds can be estimated using a method of fixed SOAs, for which a predetermined number of trials are presented for each chosen SOA (see Ben-Artzi et al., 2005 for an example). An alternative approach estimates thresholds using adaptive staircase procedures, which progressively change the distance between stimuli according to participants' response accuracy (Rose et al., 1970). With multisensory SJ and TOJ, a probability curve for performance as a function of SOA can be calculated, from which the TBW can be estimated (Fig. 1c and 1d).

1.3. Temporal processing in ASD

Sensory processing in ASD has been described both in terms of enhanced and reduced abilities (Wallace and Stevenson, 2014). For example, in the auditory modality, pitch discrimination may be enhanced (Bonnel et al., 2003), but performance in more complex tasks involving speech can be atypical or impaired (see O'Connor, 2012). Existing theories of sensory processing in ASD such as Enhanced Perceptual Functioning (Mottron et al., 2006) and Weak Central Coherence (Happé and Frith, 2006) state that low-level elements are processed more efficiently or readily in ASD compared to higher-level, more complex stimuli. These models are founded on empirical research of perceptual judgments that are not as explicitly temporal as SJ or TOJ tasks (for example, judgments of auditory pitch or visual form). However, an extension of these models to the temporal domain might predict that differences in unisensory SJ or TOJ performance would be in the direction of greater acuity in ASD, whereas the more complex aspect of sensory integration required in multisensory TOJ tasks would be in the direction of impaired performance (wider TBWs) in ASD. Additionally, Brock's (2002) binding theory is applied to ASD to explain sensory alterations, particularly with multisensory integration relating to the TBW (Thye et al., 2018). It states that temporal information is necessary to properly bind associated stimuli and that sensory stimuli that are close in time are more likely to be integrated together, and accounts for biases in sensory perception as well as language and social deficits in terms of poor integration of sensory information arising from temporal processing deficits. This theory makes the prediction for poor multisensory temporal processing in ASD. However, in current research of temporal processing in ASD, it is still unclear to what extent unisensory processing is impaired compared to multisensory processing in TOJ and SJ tasks.

The evidence for atypical unisensory temporal processing in ASD is mixed, as some studies have found increased temporal acuity and others diminished acuity. For example, adults with ASD were better able to tell the difference between simultaneous and non-simultaneous visual cues in SJ tasks compared to typically developing adults (Falter et al., 2012; Falter et al., 2013), whereas children with ASD were impaired in performing auditory TOJ but not visual TOJ (Kwakye et al., 2011). Tactile processing has also shown mixed performance in ASD, with some research showing equivalent TOJ performance to TD (Puts et al., 2014) and some showing impaired TOJ in ASD (Wada et al., 2014).

In contrast, multisensory temporal processing shows more consistent deficits, as measured by differences in the TBW (Foss-Feig et al., 2010; Kwakye et al., 2011; Noel et al., 2018b; Zhou et al., 2018). Most studies have found that ASD participants have larger TBWs, meaning that multisensory information is perceived as being simultaneous even when it is asynchronous by a longer period of time. On the other hand, some studies have reported no differences in TBW size for ASD (e.g., Turi et al., 2016), or only found increases when using speech stimuli (e.g., Stevenson et al., 2014). It remains unknown whether temporal processing in impaired in ASD only in specific contexts, such as task modality and stimuli type, or whether it is a more general impairment that persists across contexts.

1.4. Temporal processing in DD

It is generally understood that DD is characterised by impairments in phonological processing, comprising poor phonological awareness, poor verbal short-term memory, and slow lexical retrieval (Vellutino et al., 2004; Ramus and Szenkovits, 2008). There is debate over the potential underlying mechanisms that give rise to these phonological deficits in dyslexia (Vidyasagar and Pammer, 2009; Stein, 2018). As such, temporal processing has been targeted as a possible fundamental factor in the development of phonological processing deficits and in the manifestation of reading and writing delays in DD (e.g., Francisco et al., 2017b; Vandermosten et al., 2011). A prominent theory is the rapid auditory processing (RAP) deficit, which posits that auditory temporal impairments cause deficits in both the perception and production of speech sounds, which in turn impact basic reading and writing skills (Farmer and Klein, 1995; Tallal, 1980). A visual temporal account for DD deficits is provided by the magnocellular theory, which focuses on impaired development and functioning of the magnocellular cells that are responsible for rapid processing of visual information in the brain (Stein and Walsh, 1997). According to Stein (2018), visual timing deficits arising from magnocellular dysfunction in DD contribute to the deficits seen in reading and writing, but should be understood as one of many determining factors of literacy. Accordingly, many theories have been formulated for DD around one modality or one cause (Goswami, 2011; Hari and Renvall, 2001), while others account for deficits in multiple modalities or in different processes (Fostick and Revah, 2018; Pammer and Vidyasagar, 2005; Wolf and Bowers, 1999).

Unisensory temporal processing deficits reported in dyslexia span a broad range of auditory, visual and tactile tasks (Hämäläinen et al. 2013; Laasonen et al., 2012; Pammer, 2014). In TOJ and SJ tasks in particular, it has been shown that individuals with DD require longer SOAs to judge the order of two consecutive auditory or visual stimuli, compared to control participants (Ben-Artzi et al., 2005; Hairston et al., 2005).

In terms of multisensory temporal processing, deficits in temporal audiovisual integration have been shown with SJ and TOJ tasks and have been hypothesized to play a role in reading difficulties in DD (Hahn et al., 2014). Current data point toward a larger TBW for both speech and non-speech stimuli in DD (Laasonen et al., 2002b; Virsu et al., 2003; however, see Francisco et al., 2017b). It is still unknown whether temporal processing in DD shows equivalent impairment between the visual and auditory modalities, nor whether multisensory processing is impaired to the same extent as in unisensory processing.

1.5. Clinical symptoms and temporal processing

Temporal processing and multisensory integration are essential to form correct perceptual representations, which serve as a foundation for higher cognitive functions (Baum et al., 2015). Failing to acquire these perceptual representations might compound into higher order deficits such as the social and communicative deficits seen in ASD or reading and writing difficulties in DD.

Although these associations between fundamental temporal perception and higher level deficits have not been extensively studied in ASD, there are some examples of this work. Stevenson et al. (2018) found a relationship between multisensory temporal processing and speech perception in ASD, in which a wider TBW in a TOJ task was associated with less accurate speech-in-noise perception. Alternatively, Smith et al. (2017) showed that individuals with ASD had a narrower TBW, and within ASD a narrower TBW was associated with greater symptom severity. These studies provide evidence that temporal processing in ASD is associated with symptomatology, but the direction of this association remains unclear.

In DD, unisensory temporal processing, both auditory and visual, has been shown to correlate with phonological awareness and reading measures (Fostick and Revah, 2018; Kinsbourne et al., 1991). Similarly, the precision of multisensory temporal judgments has been shown to correlate with phonological awareness (Laasonen et al., 2002b), an essential ability for developing adequate reading and writing skills (Melby-Lervåg et al., 2012), and also predicts reading accuracy in DD (Francisco et al., 2017b). These results support the claim that temporal processing is important for reading outcomes in DD.

1.6. Age and temporal processing

In the general population, unisensory and multisensory temporal processing develops with age. Children gradually gain temporal acuity while adults become less accurate with age (Di Lollo et al., 1982; Lewkowicz, 1996; Lewkowicz and Flom, 2014), and accordingly during childhood years, the TBW narrows during childhood development (Hillock et al., 2011) and then progressively widens through the subsequent decades of life (Bedard and Barnett-Cowan, 2016; Setti et al., 2011).

As previously mentioned, individuals with ASD or DD show atypical sensory processing. Although no studies have directly investigated the relationship between temporal processing and age in ASD, evidence from the broader multisensory integration literature points to a delayed maturation of multisensory abilities (Beker et al., 2018; Feldman et al., 2018; Foxe et al., 2013). For example, young children with ASD fail to perceive the McGurk illusion, an audiovisual integration task that is usually perceived in TD children. This illusion is perceived by older children and adolescents with ASD, which is indicative of successful multisensory integration that “catches” up with TD individuals (Taylor et al., 2010).

In DD, temporal processing shows a developmental pattern that is comparable to typical development. Specifically, temporal acuity is positively correlated with age during childhood (Lorusso et al., 2014; Wang and Yang, 2018) and negatively correlated with adult aging (Hairston et al., 2005; Virsu et al., 2003).

1.7. Previous reviews of temporal processing in ASD and DD

Unisensory temporal processing in ASD has received less focus than multisensory processing. A recent systematic review of time perception by Casassus et al. (2019) notes impairments in unisensory temporal performance in ASD but also points to inconsistencies across individual study results. Additionally, a meta-analysis of temporal binding by Zhou et al. (2018) was not able to test for impairments specific to unisensory temporal processing in ASD because of the inclusion of only two such unisensory studies in their review. Many questions therefore remain open about unisensory temporal processing in ASD, including the extent of any impairments as well as patterns of ability related to specific sensory modalities.

In recent years, a great amount of research has focused on multisensory integration in ASD. One narrative review (Beker et al., 2018) and two meta-analyses (Feldman et al., 2018; Zhou et al., 2018) have summarized findings related to audiovisual integration and temporal binding in the last year. However, it should be noted that only Zhou et al. focused specifically on temporal processing, and their meta-analysis only included four multisensory studies. These reviews generally agree on the presence of multisensory temporal processing impairments in ASD, which can manifest as increased multisensory TBWs as well as impaired performance on a wide range of audiovisual tasks. Specifically, Beker et al. (2018) observed a developmental pattern in which impairments were present in multisensory functions during childhood but progressively resolved during late adolescence and adulthood. Feldman et al.

(2018) came to a similar conclusion in their meta-analysis of audiovisual integration, showing that group differences between ASD and TD were more evident during childhood. In contrast, Zhou et al. (2018) did not find any relation with age and temporal binding, but this may result from a limited amount of available data (six studies).

Several previous narrative reviews have examined temporal processing in DD in terms of unisensory auditory processing and multisensory integration. Farmer and Klein (1995) and Studdert-Kennedy and Mody (1995) each review evidence for auditory temporal processing impairments, the first one supporting Tallal's RAP theory (1980) leading to reading deficits, and the second arguing against it. Rosen's (2003) review on auditory processing in DD and specific language impairment discusses the possibly limited role of auditory processing deficits in DD's language impairment. To date, there are no systematic reviews or meta-analyses in unisensory auditory or visual processing in DD in the context of the SJ and TOJ tasks. More recently, a review of multisensory integration in DD supports the claim that deficits are present and result in an increased TBW (Hahn et al., 2014). No quantitative review of multisensory processing or TBW has been undertaken in DD.

1.8. The present systematic review and meta-analysis

The current review takes a systematic and quantitative approach to examine temporal processing in ASD and DD, encompassing both unisensory and multisensory temporal processing using the SJ and TOJ tasks. As such, this is the first quantitative review to bring together two neurodevelopmental disorders in order to better understand temporal processing. The focus on two specific, commonly used temporal perception tasks helps to assess consistency and specificity across prior research, and provides a foundation to better understand patterns of deficits across unisensory processing, temporal binding and multisensory integration in ASD and DD. Previous evidence for poor temporal acuity and atypical TBW sizes in ASD and DD suggests deficits in both unisensory and multisensory temporal processing. However, it remains unclear whether these deficits are consistent across both disorders and how they vary across different contexts and variables such as symptom severity and age.

The systematic review component of the present study provides a description of the sample populations used in both ASD and DD studies separately, as well as the main tasks and modalities investigated. In conjunction with the systematic review, a quality assessment was performed that assessed key methodological aspects of the studies in terms of sample definitions, group matching, and use of appropriate task parameters.

The quantitative meta-analyses evaluated the evidence for temporal processing deficits in ASD and DD in terms of overall performance as well as across specific task contexts such as modality in both ASD and DD (auditory, visual and tactile), processing type in ASD (multisensory or unisensory), and stimulus type in ASD (speech or nonspeech). It was expected that temporal processing would be impaired in ASD (Kwakye et al., 2011; Noel et al., 2018a) and DD (Laasonen et al., 2001; Hairston et al., 2005), with modality specific impairments for ASD and DD.

ASD was expected to show both poorer unisensory acuity and multisensory temporal performance (larger TBWs). Speech stimuli in ASD were expected to be associated with greater deficits compared to nonspeech stimuli, because of increased processing complexity required for speech (Beker et al., 2018). Speech stimuli were not investigated in DD because of a lack of studies meeting criteria for comparability (see section 2.1).

A second aim in the meta-analyses was to investigate the relation between temporal processing and symptom severity in ASD and DD. It was expected that temporal processing would be associated with symptom severity for both disorders, such that poor temporal acuity and larger TBWs would be related to greater symptom severity in ASD (Brandwein et al., 2015; Stevenson et al., 2018) and DD (Francisco et al., 2017b).

A third aim in the meta-analyses was to examine the relation between temporal processing and age. It was expected that measures of temporal acuity would follow a developmental trajectory similar to what is seen in typical development, such that processing improves during childhood and degrades with aging (Hillock et al., 2011; Bedard and Barnett-Cowan, 2015).

2. Methods

2.1. Rationale for study criteria

The overall scope of this systematic review and quantitative meta-analysis was defined in terms of the 1) clinical groups and 2) task measures used in the reviewed research. All studies examined temporal processing in individuals with ASD or DD using a TOJ or SJ task.

Studies in ASD were required to mention confirmation of diagnosis by standardized diagnostic instrument (Autism Diagnostic Observation Schedule (ADOS; Lord et al., 1989), Autism Diagnostic Interview (ADI-R; Le Couteur et al., 1989)) or expert clinical diagnosis.

In DD, measurable impairments manifest somewhat differently depending on the nature of a language, and DD diagnoses differ in criteria across different countries (Peterson and Pennington, 2012). Accordingly, an inclusive approach was taken in the literature search. Studies in DD could include individuals with a clinical DD diagnosis as well as individuals meeting DSM-5 diagnosis criteria for Specific Learning Disorder. Additionally, DD groups could include non-diagnosed individuals whose performance on common reading and spelling tasks was at least one standard deviation below a typically developing control group. An IQ-achievement discrepancy was not necessary.

TOJ or SJ tasks were expected to use stimulus onset asynchronies (SOA) or inter-stimulus intervals (ISI) short enough that the difficulty in the task mainly arises from the stimulus timing. Tasks that only used large stimulus onset intervals (SOA of above 30 ms) were not considered to be comparable (for example, see criticism in Studdert-Kennedy and Mody (1995), or Wittmann and Fink (2004) on methodological issues in rapid auditory perception in DD), and were not included.

2.2. Search strategy

An exhaustive search for published studies between April 1980 and April 2019 was performed in the following online databases: PsycINFO, Scopus, Pubmed, Web of Science, and ProQuest Dissertations and Theses Global. The keywords used in these searches were: (“ASD”, “autis*”, “asperger*”, or “dyslexi*”) AND ((“temporal order judg*”, “simultaneity judg*”, “TOJ”, or “SJ”) OR (“temporal processing”, “temporal integration”, “temporal binding”, or “temporal window of integration”)). The first section of keywords refers to the two clinical populations that were of interest for the meta-analysis. The second section identifies terms relevant to the two tasks targeted by this meta-analysis, and terms that are frequently used in the literature to refer to temporal processing and the TBW (Zhou et al., 2018). A Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA; Liberati et al. 2009) diagram summarizing the number of studies meeting the search criteria is shown in Fig. 2.

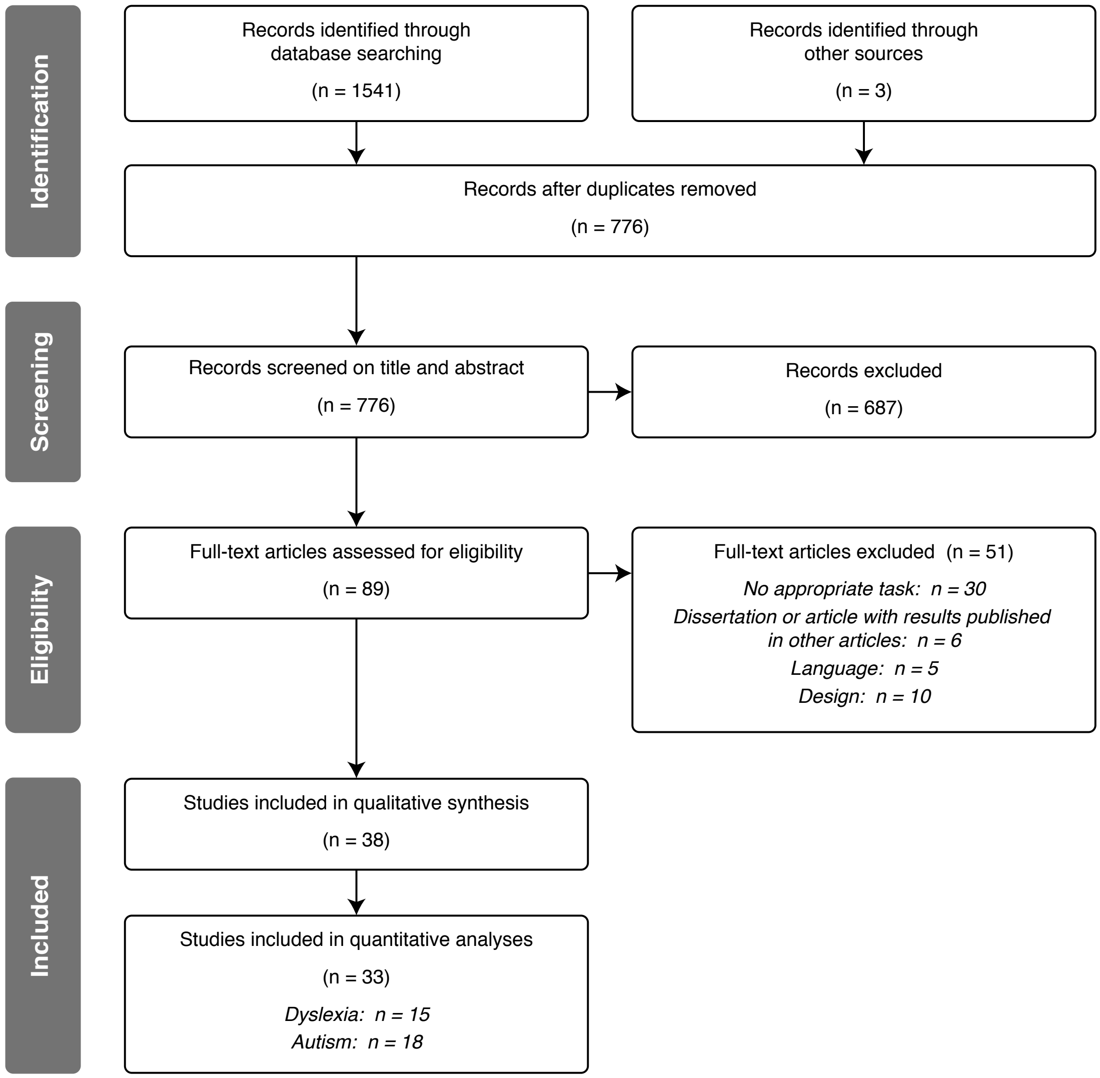

Fig. 2. PRISMA chart showing the number of included studies for the qualitative and quantitative components of the review.

2.3. Study selection

All search results were exported into EndNote software (version X8; Clarivate Analytics, New York, USA). The records were inspected for duplicates and remaining unique records were kept and evaluated according to the inclusion criteria. Titles and abstracts were screened according to the four following criteria, following this order:

1. Population: Studies that did not include a human clinical group corresponding to ASD or DD were excluded (see further information in section 2.1). A total of 280 studies were discarded based on this criterion.
2. Topic: Studies outside of the topic of sensory processing and temporal processing were excluded. A total of 214 studies were discarded based on this criterion.
3. Design: Studies were excluded if their design did not correspond to an empirical study. Descriptive or observational studies were excluded, as well as reviews or opinion articles. A total of 61 studies were discarded based on this criterion.
4. Task: Studies with tasks that did not correspond to a TOJ or SJ paradigm were excluded. A total of 155 studies were discarded based on this criterion.

A total of 89 studies were then assessed for inclusion based on data extracted from the full text as described below; this was the "coding set". The study selection evaluated at the full-text stage used the 4 criteria listed above, as well as 1) article language (English, French or Spanish), 2) participant sample not overlapping with another study, 3) presence of a typically-developing control group, 4) appropriate task parameters (see section 2.1), and 5) reporting of necessary quantitative data in text, tables or figures in order to calculate effect sizes. The numbers of studies subsequently excluded from the coding set based on these criteria are described in the results section 3.1.

2.4. Data extraction

The 89 studies in the coding set were extracted for data by the first author, and a randomly selected sample was also examined by a second researcher (SMC) (50 studies; 56%). Inter-rater agreement on this subset was 90%. Data were also extracted for studies included in the qualitative review, in order to qualitatively describe the literature regardless of the availability of quantitative values for meta-analysis.

The data extraction process compiled information from each article across six categories: (a) quantitative data for calculation of effect sizes from temporal processing measures relevant for the present meta-analyses (threshold, accuracy, TBW width), (b) experimental design (sensory modality, task trials, SOAs, etc), (c) group diagnostic definitions (e.g. ASD, Asperger syndrome, DD), (d) group demographic characteristics (age, gender, country, IQ, language), (e) sample sizes for each included group, and (f) symptom severity scores (ADOS or Social Responsiveness Scale (SRS; Constantino and Gruber, 2005) for ASD; reading speed and accuracy for DD). Eligible data for group comparisons were group means (with standard deviations, confidence intervals, or standard errors of the mean) and t-values. Eligible data for the relation between temporal processing and symptom severity or age were Pearson correlations; in this case, only correlations within the clinical group were considered. In other words, correlations that were calculated over the whole sample (including the control group) were excluded. Authors were contacted to request missing data, clarification of methods, or availability of unpublished data. A data-sharing agreement form based on Polanin and Terzian (2019) was sent to the contacted authors via email. The purpose of this form was to increase author responsivity and willingness to share their data, by clearly stating the terms under which their data is used. Response rate was 43%.

In addition, the WebPlotDigitizer software version 4.2 (Rohatgi, 2019) was used to obtain means and standard deviations (or standard errors of the mean) when these values were presented in graphs but not reported in text or tables (8 studies).

2.5. Quality assessment

The 33 studies that met the inclusion criteria after data extraction were evaluated for research quality and reporting quality. The purpose of this quality assessment process was to identify potential areas of improvement for research methods and reporting standards in future studies. The quality assessment scale was adapted from the Newcastle-Ottawa scale for Assessing the Quality of Nonrandomized Studies in Meta-Analysis (Wells et al., 2014) and was similar to the assessment used by Zhou et al. (2018). Three sections were evaluated: selection of participants, matching between groups (age, IQ, gender, and socio-economic status/education), and task (number of SOAs, trials per SOA, staircase procedure parameters, etc.). A score of one was given if the desired criterion was present, and zero if this criterion was absent from the study. The maximum score of the quality assessment scale was eight.

2.6. Analyses

Following meta-analytic guidelines (Lipsey and Wilson 2001), a rigorous synthesis and analysis of the set of studies was performed. For each analysis, effect sizes were calculated as Hedges' *g* for group comparisons and Pearson's *r* for correlations with clinical severity, using Comprehensive Meta-Analysis software version 2.0 (Borenstein et al., 2005) as necessary. When a study reported multiple outcomes that were relevant for a particular analysis (i.e. measured within the same participants), an effect size was calculated for each outcome and these were then combined by performing a supplemental meta-analysis to obtain a single effect for the study. The same approach was used for studies with identical samples measuring different outcomes. Specifically, the measures from Laasonen et al. (2001) and Laasonen et al. (2002b), as well as Laasonen et al. (2002a) and Virsu et al. (2003), were combined for the main DD analysis because they had identical samples but different measures (unisensory and multisensory).

Random-effects meta-analyses of the effect sizes were performed in R version 3.3.2 using the “metafor” package (Viechtbauer, 2010), at a significance criterion of $p < .05$. Analyses with metafor used the “rma.uni” function, except as noted. The random-effects approach accounts for variation across studies and is recommended when studies vary in their samples or methodology (Borenstein et al., 2009). Moreover, random effects provide for greater control for differences in sample size when estimating effect sizes (Borenstein et al. 2009). Between-study heterogeneity was estimated using the restricted maximum likelihood (REML) method and confidence intervals of effect sizes were estimated using the Q-profile method, following the recommendations of Veroniki et al. (2015). For ease of description, effect sizes are labeled in the text as “small” (g ~ 0.2; r ~ 0.1), “medium/moderate” (g ~ 0.5; r ~ 0.3) or “large” (g ~ 0.8; r ~ 0.5) following Cohen (1988); it is understood that these labels are approximate and their values may vary by research domain.

To answer the aim examining temporal processing in ASD and DD compared to TD, Hedges’ g effect sizes (Higgins and Green, 2006) were calculated. To ensure consistency of effect size direction across different measures, effect sizes representing impairment (poorer temporal processing) in the clinical (ASD or DD) group were given a positive sign, and effects representing greater ability (better temporal processing) in the clinical group were given a negative sign. In addition to the overall group comparisons in ASD and DD, separate analyses were run for within each clinical group, according to task modality and stimuli. For ASD, separate analyses were run for unisensory and multisensory tasks, tactile and visual tasks, as well as tasks using speech and nonspeech stimuli. As for DD, separate analyses on auditory, tactile and visual tasks were conducted, along with an analysis grouping multisensory tasks. These analyses estimated the effect size of temporal processing differences between the clinical and control group for each particular type of task.

In order to quantitatively compare effect sizes between different types of tasks (e.g., between multisensory and unisensory tasks in the comparison between ASD and TD), multivariate linear mixed-effects models were run using the "rma.mv" function in the metafor package in R. In these analyses, the task type was set as a moderator. An individual study could provide an effect size for each type of task (if available), and the covariance within studies was modeled using compound symmetry in the rma.mv function. Specifically, in ASD, effect sizes were compared between multisensory and unisensory tasks, and between speech and nonspeech task conditions. In DD, effect sizes were compared between tasks in the auditory and visual modalities.

For the analyses of the effects of clinical severity in ASD and DD, Pearson correlations reported by studies were converted to the Fisher's *z* scale using the Fisher transformation (Borenstein et al., 2009). A positive effect represented greater ability (better temporal processing) associated with better outcomes (i.e., lower symptom severity in social communication in ASD, better reading and writing skills in DD). Inversely, a negative effect represented greater temporal acuity associated with worse outcomes (i.e., worse symptom severity in social communication in ASD, worse reading and writing skills in DD).

Mixed effects meta-regressions were undertaken to investigate the potential role of age in moderating temporal processing performance in ASD and DD separately. The mean ages of ASD and DD groups were taken from individual studies, as tested as predictors of temporal processing differences (ASD vs TD, or DD vs TD).

In consideration of the high proportion of studies that did not explicitly match gender between groups, as identified in the present systematic review, additional analyses were conducted to test whether effect sizes differed based on gender matching status (i.e., matched versus unmatched), by adding matching status as a moderator in the multivariate linear mixed-effects models.

2.6.1. Heterogeneity measure

Heterogeneity across studies was assessed using the I^2 measure (Higgins and Green 2006). This measure is sensitive to whether differences in results across studies are due to measuring different effects or attributable to chance, and is recommended by Cochrane Reviews (Higgins et al. 2003). I^2 values of 25% indicate a low percentage of heterogeneity, 50% indicates moderate heterogeneity and 75% indicates a high percentage of heterogeneity. Forest plots were created to display all the effect estimates and confidence intervals for both individual studies and meta-analyses (Lewis, 2001). These plots also provide an indication of heterogeneity between studies (Phan et al. 2015).

2.6.2. Publication bias

Publication bias refers to the increasing probability of a study being published as the effect size of its findings increases. In order to minimize the presence of publication bias in this meta-analysis, a search for non-published work was performed in the ProQuest Dissertations and Theses Global online database, and all authors included in the analyses were contacted for any unpublished data.

Two techniques were used to assess the presence of publication bias. First, as a visual diagnostic, funnel plots were generated to present the effect size of individual studies against the standard error associated with each study. Asymmetry around the triangular funnel may indicate the presence of publication bias (Rothstein et al., 2006). Second, as a quantitative diagnostic, Duval and Tweedie's L0 trim and fill procedure was used to impute additional effect values as necessary to correct asymmetry (Duval and Tweedie, 2000), closely approximating an unbiased distribution (Borenstein et al., 2009).

3. Results

3.1. Study selection

The final sample included in the review comprised 38 studies (21 ASD; 17 DD). An additional 51 studies were assessed for inclusion but were excluded for the following reasons: overlapping samples with another study (n = 6), no comparable TD group or inadequate design (n = 10), written in another language than English, French or Spanish (n = 5), or lack of adequate SJ or TOJ task (n = 30). Included studies varied in publication status (one unpublished dissertation), country and in participants' native languages. There were 13 studies originating from the United States, 7 from the United Kingdom, 6 from Finland, 4 from Israel, 3 from the Netherlands, 2 from Japan, and 1 from each China, Italy and Poland. Participants' native language for the ASD sample was mostly English (15), then Japanese (2), Dutch (2), Italian (1), and Finnish (1). The DD sample was more varied, with English (5), Finnish (5), Hebrew (4), Dutch (1), Chinese (1), and Polish (1).

There were 33 studies included in the meta-analysis (18 ASD; 15 DD), as 5 studies did not have the necessary data to calculate an effect size and were only included in the qualitative review (see Table 1 and 2).

Table 1
Study characteristics for the ASD sample

	ASD			TD			Study methods			
Study Name	n (% male)	Mean age (SD)	Mean IQ (SD)	n (% male)	Mean age (SD)	Mean IQ (SD)	Modality	Task	Stimuli	Outcome
de Boer-Schellekens et al. (2013a)	15 (67)	19.2 (2.4)	106.2 (14.2)	15 (67)	19.3 (1.3)	106.6 (8.4)	AV	TOJ	Flash/beep, handclap, syllables	Threshold
de Boer-Schellekens et al. (2013b)	33 (NR)	18.8 (2.1)	103.2 (14.6)	37 (NR)	18.8 (1.3)	107.9 (9.1)	V	TOJ	Two white squares	Threshold
Falter et al. (2013)	16 (94)	24.1 (7.0)	115.0 (11.0)	17 (77)	26.3 (6.5)	117.0 (9.0)	V	SJ	Two white bars	Synchrony responses
Ide et al. (2019)	13 (85)	19.1 (NR)	103.5 (NR)	13 (69)	21.2 (NR)	118.3 (NR)	T	TOJ	Two vibrations	Threshold
Isaksson et al. (2018)	15 (87)	11.0 (2.3)	100.0 (18.0)	16 (81)	10.3 (1.6)	109.0 (10.0)	V	SJ	Two angry bird images	Threshold
Kwakye et al. (2011)	34∴ (85)	12.2 (2.7)	102.9 (18.7)	27 (81)	11.7 (2.4)	109.5 (10.8)	A, V	TOJ	Clicks; Open circle	Threshold
Noel et al. (2017a)	26 (92)	12.3 (3.1)	110.2 (14.1)	26 (46)	11.6 (3.8)	111.5 (14.7)	AV	SJ	Flash/beep, hand tool, syllables	TBW
Noel et al. (2017b)	12 (67)	12.2 (3.8)	106.3 (18.3)	15 (73)	10.9 (2.1)	111.6 (19.5)	AV	SJ	Two syllables	TBW
Noel et al. (2018a)	23 (65)	22.0 (4.2)	101.9 (13.5)	31 (52)	NR (NR)	NR (NR)	AV	SJ	White ring, pure tone	TBW
Poole et al. (2018)	22 (NR)	30.4 (7.8)	117.7 (8.2)	22 (NR)	31.0 (8.9)	115.1 (9.4)	VT	TOJ	Flash, vibration	Threshold
Puts et al. (2014)	27 (82)	10.7 (1.2)	103.1 (14.9)	54 (76)	10.08 (1.3)	117.3 (12.2)	T	TOJ	Two vibrations	Threshold
Regener (2015)	24 (NR)	26.6 (7.0)	117.5 (11.14)	25 (NR)	25.81 (5.9)	119.1 (8.6)	AV	SJ, TOJ	Flash/beep, face/voice, drumming	TBW
Smith et al. (2017)	20 (90)	14.6 (2.2)	111.5 (15.6)	20 (90)	14.0 (1.9)	109.3 (10.9)	AV	SJ related	Two syllables	TBW
Stevenson et al. (2014)	38 (91)	11.8 (3.2)	57.5* (8.4)	38 (59)	12.3 (2.3)	53.7* (8.0)	AV	SJ	Flash/beep, tools, syllables	TBW
Stevenson et al. (2018)	32 (84)	12.3 (3.1)	48.5* (NR)	32 (34)	11.1 (2.7)	47.3* (NR)	AV	TOJ	Flash/beep	TBW
Tommerdahl et al. (2008)	10 (100)	26.1 (6.3)	102.8 (17.7)	20 (NR)	24.2 (6.1)	115.6 (7.1)	T	SJ, TOJ	Two vibrations	Threshold
Turi et al. (2016)	16 (75)	29.2 (5.2)	112.0 (10.3)	16 (81)	27.1 (2.8)	112.7 (11.4)	AV	SJ	Two white rings	TBW
Wada et al. (2014)	10 (80)	11.8 (0.7)	100.7 (6.5)	10 (70)	11.7 (0.7)	101.6 (2.4)	T	TOJ	Two vibrations	Threshold

A = Auditory, T = Tactile, V = Visual, AV = Audiovisual, AT = Audiotactile, NR = Not reported, VT = Visuotactile, *Matrix reasoning t-score.

Table 2
Study characteristics for the DD sample

Study Name	DD			TD			Study methods			
	n (% male)	Mean age (SD)	Mean IQ (SD)	n (% male)	Mean age (SD)	Mean IQ (SD)	Modality	Task	Stimuli	Outcome
Ben-Artzi et al. (2005)	23 (26)	25.6 (NR)	NR	26 (27)	22.7 (NR)	NR	A	TOJ	Two pure tones	Accuracy
Chen et al. (2016)	17 (35)	10.0 (0.2)	NR	20 (40)	10.2 (0.2)	NR	V	TOJ	Two black circles	Threshold
Fostick et al. (2014a)	51 (63)	26.6 (4.2)	NR	18 (72)	25.6 (3.3)	NR	A	TOJ	Two pure tones	Threshold
Fostick & Revah (2018)	78 (55)	25.3 (2.3)	NR	23 (35)	22.8 (1.6)	NR	A	TOJ	Two pure tones	Threshold
Francisco et al. (2017a)	53 (76)	22.6 (2.7)	10.5* (2.22)	52 (79)	22.1 (2.7)	9.9* (2.45)	AV	SJ	Syllables	Synchrony responses
Hairston et al. (2005)	36 (64)	NR	NR	29 (55)	NR	NR	V	TOJ	Two white circles	Threshold
Jaskowski & Rusiak (2008)	21 (48)	21.1 (2.1)	75.4* (21.6)	21 (19)	22.1 (2.2)	85.9* (14.7)	V	TOJ	Two rectangles	Accuracy
Kinsbourne et al. (1991)	23 (NR)	29.3 (8.8)	110.8 (15.5)	21 (NR)	26.5 (7.7)	112.7 (13)	A, V	TOJ	Two lights	Threshold
Laasonen et al. (2001) / Laasonen et al. (2002b)	16 (25)	26.9 (5.3)	109.1 (8.7)	16 (44)	25.1 (5.1)	115.1 (9.3)	A, T, V, AV, AT, VT	TOJ	Flash, tones, skin indentation	Threshold
Laasonen et al. (2002a) / Virsu et al. (2003)	39 (26)	37.0 (11.7)	107.3 (11.5)	40 (35)	36.0 (11.9)	115.0 (11.1)	A, T, V, AV, AT, VT	TOJ	Flash, tones, skin indentation	Threshold
Laasonen et al. (2012)	38 (26)	36.7 (11.7)	107.2 (8.5)	40 (35)	36.1 (11.9)	113.3 (10.9)	A, V, T	TOJ	Flash, tones, skin indentation	Threshold
May et al. (1988)	7 (NR)	9.1 (NR)	105.4 (12.1)	7 (57)	9.0 (NR)	112.1 (16.8)	V	TOJ	Two white words	Threshold
Pasquini et al. (2007)	18 (NR)	21.6 (2.3)	115.2 (6.5)	18 (NR)	22.0 (2.4)	117.2 (7.0)	A	TOJ	Two sounds (dog, car)	Threshold

A = Auditory, T = Tactile, V = Visual, AV = Audiovisual, AT = Audiotactile, NR = Not reported, VT = Visuotactile, SJ = Simultaneity judgment, TOJ = Temporal order judgment, *WAIS-IV matrix reasoning standard score (Francisco et al., 2017a); Ravens matrices test's standard score (Jaskowski et al., 2008).

Table 3
Summary of studies included in the symptom severity analyses

Study Name	Participant sample				Severity measure			
	Clinical group	Mean age (SD)	Mean IQ (SD)	N	Modality	Type of outcome	Severity tool/task	Pearson correlation
Ide et al. (2019)	ASD	19.1 (NR)	103.5 (NR)	13	T	Social and communication, restricted behavior	ADOS-2	0.07
Isaksson et al. (2018)	ASD	11.0 (2.3)	100.0 (18.0)	15	V	Social and communication, restricted behavior	ADOS	-0.64
Smith et al. (2017)	ASD	14.6 (2.2)	111.5 (15.6)	20	AV	Social and communication, restricted behavior	SRS	-0.43
Ben-Artzi et al. (2005)	DD	25.6 (NR)	NR	23	A	Reading errors	Text reading	-0.24
Fostick et al. (2014)	DD	26.6 (4.2)	NR	51	A	Correct words read per minute	One-minute test for pseudo-words	0.42
Fostick & Revah (2018)	DD	25.3 (2.3)	NR	78	A	Correct words read per minute	One-minute test for pseudo-words	0.31
Francisco et al. (2017a)	DD	22.6 (2.7)	10.5* (2.22)	53	AV	Reading errors	Text reading	0.21
Kinsbourne et al. (1991)	DD	29.3 (8.8)	110.8 (15.5)	23	A, V	Spelling accuracy	WRAT	0.43

A = Auditory, T = Tactile, V = Visual, AV = Audiovisual, AT = Audiotactile, NR = Not reported, SJ = Simultaneity judgment, TBW = Temporal binding window, TOJ = Temporal order judgment, ADOS = Autism diagnostic observation schedule, SRS = Social responsiveness scale, WRAT = Wide range achievement test. *WAIS-IV matrix reasoning standard score.

3.2. Qualitative systematic review

3.2.1. ASD study sample description

In the ASD sample (k = 21), half the studies described their ASD sample as “autism spectrum disorder”, and the other half as “high functioning autism” or “asperger”. Moreover 14 did not mention medication in its participant sample, 1 stated that none of the participants were using medication, 2 excluded participants receiving medication, and 4 included them. Participants with comorbid neurological or psychiatric disorders were excluded in 7 studies (33%) and included in 1 study (5%; Puts et al., 2014). Presence or absence of comorbid disorders was not mentioned in 7 studies (33%), and the sample was described as having no such disorders in 6 studies (29%). Mean IQ for the ASD group across studies ranged between 100.0 and 117.7 (mean of 107.2) and mean age ranged from 10.7 to 30.4 (mean of 18.0). There was an overall mean of 83% males in the ASD groups, ranging from 67% to 100% in individual studies.

Out of the 21 ASD studies, 9 studies assessed unisensory processing (43%; 3 visual, 4 tactile, 1 auditory/visual), and 12 studies assessed multisensory processing (57%; 11 audiovisual, 1 visuotactile, and 1 audiovisual/audiotactile/visuotactile). About half the studies used SJ tasks (48%), and 52% used TOJ tasks. The majority of studies (81%) measured temporal perception across a predefined set of SOAs, whereas four studies (19%) used a staircase procedure to estimate a single temporal perception threshold.

Of the 21 studies, nine studies found significant temporal processing impairments in the ASD group compared to TD, nine studies found no significant difference between groups, two found an advantage for ASD in visual processing, and one found impairments in ASD for audiovisual processing but only for speech stimuli. Across these results, there was no apparent pattern suggesting specificity of group differences to a particular type of task or modality.

3.2.2. DD study sample description

In the DD sample (k = 17), two studies described their sample as “phonological dyslexia”, one as “poor readers” (May et al., 1988), and others simply as “dyslexia” or “developmental dyslexia”. Generally, no mention of medication was made, except for one study (Laasonen et al., 2012) that stated that no medications affecting the central nervous system were taken by participants during the study. Comorbidities, neurological or psychiatric disorders were excluded in 7 studies (41%), were not mentioned in 5 studies (28.5%), and were absent in the participant samples in 5 studies (28.5%). Mean IQ was 109.2 (105.4 to 115.2) and mean age was 24.3 (9.1 to 37.0). The average percentage of males was 42%, ranging from 25% to 75%.

Of all DD studies, 13 studies were unisensory (76%; 5 auditory, 6 visual, 2 auditory/tactile/visual), 3 were multisensory (18%; 1 audiovisual, 2 audiovisual/audiotactile/visuotactile), and 1 (6%) assessed both unisensory and multisensory processing in all three modalities (Laasonen et al., 2012). Most studies used a TOJ paradigm (94%) and only one study used a SJ task (6%). Ten studies in total (59%) used a staircase procedure to estimate a perception threshold and seven (41%) measured temporal perception using a predefined set of SOAs or ISIs.

All reviewed studies found DD impairment compared to the TD group, although not in every modality examined. In particular, there were mixed results for tasks including visual stimuli, wherein two studies did not find differences between DD and TD when measuring visual processing or audiovisual/visuotactile performance using TOJ paradigms (Laasonen et al., 2001; Laasonen et al., 2002b).

3.3. Quality assessment

Overall quality of included studies was satisfactory in both clinical groups. A mean of 6.95 (SD = 0.94, median = 7.00) and 5.89 (SD = 1.28, median = 6.00) in ASD and DD respectively was found out of 8 points on the quality assessment scale. No study was excluded based on the quality assessment results.

A sample size of at least 20 participants was present in 21 studies (55%), and only 5 studies had fewer than 15 participants (13%). Groups were matched on age apart from two studies in DD (Fostick et al., 2014b; Fostick and Revah, 2018), and all studies reported age except for one (Hairston et al., 2005). Studies were mostly matched for IQ in the ASD sample, whether on the basis of full-scale or non-verbal IQ scores (see Table 1). The only ASD study not explicitly matched on IQ was Noel et al. (2018a), in which IQ was evaluated and reported for the ASD group but not the TD group. In DD, only seven studies (41%) demonstrated or stated that DD and TD groups were matched on IQ, and 6 studies failed to report IQ values. Gender was explicitly matched in 21 studies in total (55%), and reported for 32 studies (84%). Given the low proportion of studies matching for gender, supplementary analyses were conducted to examine the potential impact of gender matching on temporal processing, as described in the Methods (2.6) and reported below (3.4.1 and 3.4.2). Education and socioeconomic status were typically not mentioned in ASD studies, and were reported and matched in approximately half of the DD studies. Finally, task quality was judged as poor in 12 studies overall (32%), for reasons such as fewer than four SOAs, fewer than 15 trials per SOA, or inadequate description of tasks.

3.4. Quantitative meta-analyses

Of the 38 studies included in the qualitative review, three studies in ASD could not be included in the meta-analysis because only non-parametric tests were reported (Falter et al., 2012; Noel et al., 2018b; Poole et al., 2017), and two studies in DD reported insufficient data to calculate an effect size (Fostick et al., 2014b; Liddle et al., 2009). The table in the Appendix indicates which study was included in each analysis.

3.4.1. Group differences between ASD and TD

Across all ASD studies, a moderate overall effect size of $g = 0.52$ (k = 18; SE = 0.15; 95% CI [0.23, 0.80]; $p < .001$; Fig. 3) was found between ASD and TD. This effect indicates an overall deficit in temporal processing across different modalities and stimuli in ASD compared to TD.

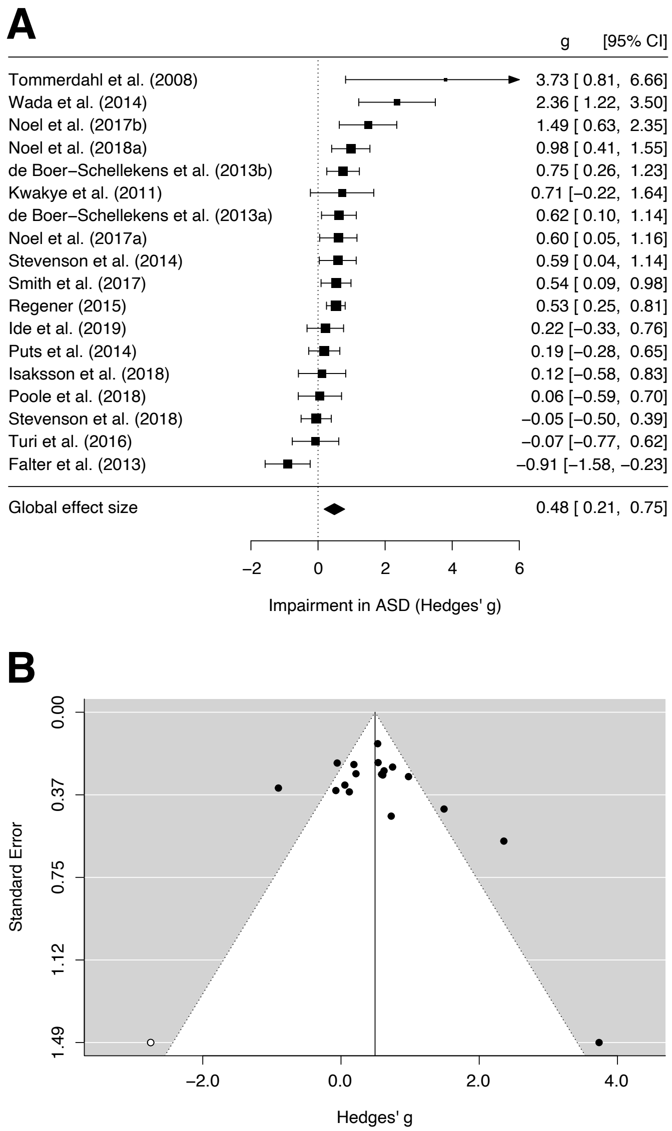

Fig. 3. Forest plot showing study effect sizes and meta-analysis result for overall temporal processing group differences in ASD (a), and funnel plot with Hedges' g values plotted against the standard error value of each effect (b).

In order to examine this effect in more detail, separate meta-analyses were conducted for unisensory (*k* = 8) and multisensory (*k* = 10) tasks. For unisensory processing, a nonsignificant effect size of *g* = 0.57 (SE: 0.36; 95% CI [-0.13, 1.28]; p = .111; Fig. 4a) was found; although this estimate is larger than for the overall analysis, the wide confidence interval reflects considerable variability within and across studies of unisensory processing. The analysis of multisensory tasks yielded a moderate effect size of *g* = 0.50 (SE = 0.12; 95% CI [0.26, 0.73]; *p* < .001; Fig. 4b), showing that individuals with ASD are impaired in making multisensory temporal judgments compared to the TD group. An additional analysis indicated no significant difference between multisensory and unisensory processing (*p* = .834).

Separate analyses were conducted for the tactile (*k* = 4) and visual (*k* = 4) modalities, in order to tease apart the unisensory analysis. Both tactile (*g* = 1.24; SE = 0.74; 95% CI [-0.20, 2.70]; *p* = .090) and visual (*g* = 0.08; SE = 0.34; 95% CI [-0.60, 0.75]; *p* = .814) modalities yielded nonsignificant effect sizes, although these should be interpreted carefully due to small samples (*k* = 4) and large confidence intervals.

Separate analyses were also performed for nonspeech (*k* = 12) and speech (*k* = 6) stimuli. A small effect indicated that temporal processing is impaired with nonspeech stimuli in ASD (*k* = 12; *g* = 0.30; SE = 0.14; 95% CI [0.02, 0.58]; *p* = .035; Fig. 4c). Additionally, a moderate effect size was found for temporal processing of speech stimuli, reflecting an impairment in ASD compared to TD (*g* = 0.71; SE = 0.12; 95% CI [0.48, 0.94]; *p* < .001; Fig. 4d). A larger effect size was found for speech processing (*g* = 0.71) compared to nonspeech processing (*g* = 0.30), a difference that was significantly different when tested within a hierarchical meta-analysis model (*p* = .048).

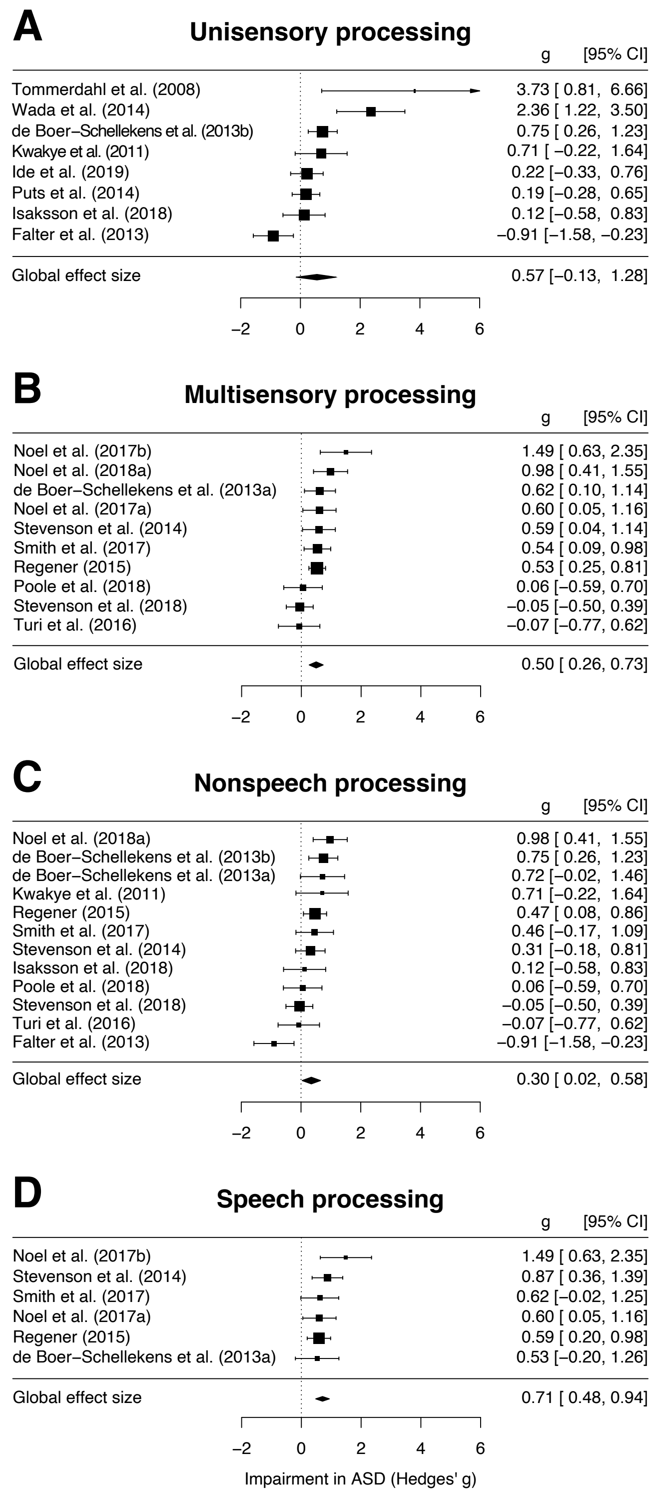

Fig. 4. Forest plots showing study effect sizes and meta-analysis results for group comparisons of (a) unisensory temporal processing, (b) multisensory temporal processing, (c) nonspeech temporal processing, and (d) speech temporal processing in ASD.

3.4.2. Group differences between DD and TD

Across all DD studies, a large overall effect size of *g* = 0.82 (*k* = 13, SE = 0.08; 95% CI [0.64, 0.99]; *p* < .001; Fig. 5) was found between DD and TD. This indicates an overall impairment in making temporal judgments in DD. Although gender matching status was found to influence the effect size in DD (*p* < .001), such that gender matched studies were associated with smaller effect sizes (*g* = 0.59; moderate effect) compared to studies that did not match on gender (*g* = 1.05; large effect), temporal processing deficits were significant in both types of study.

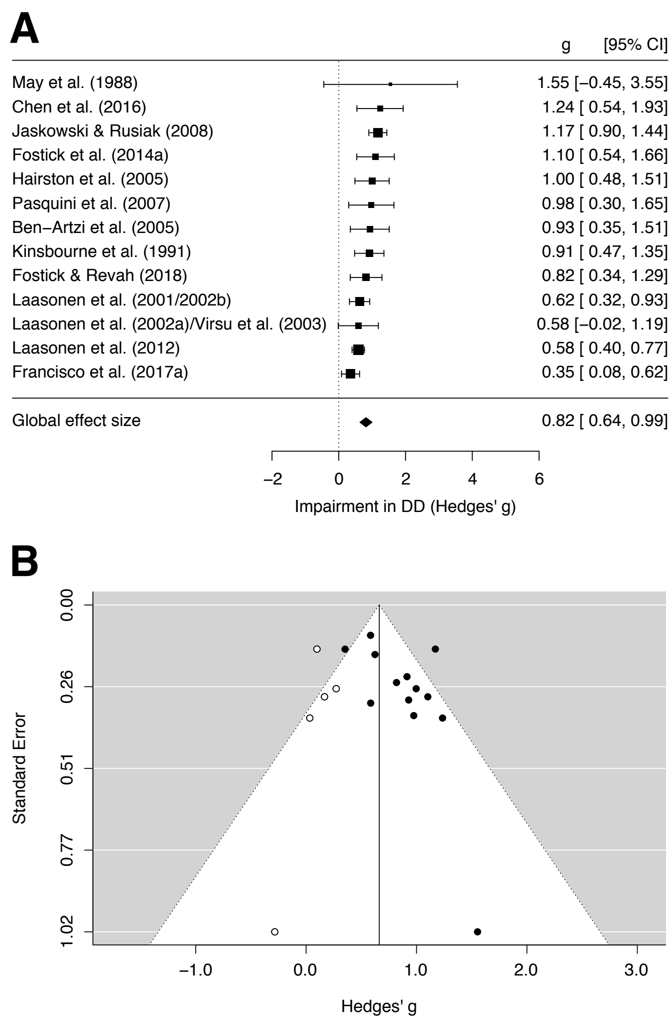

Fig. 5. Forest plot showing study effect sizes and meta-analysis result for overall temporal processing group differences in DD (a), and and funnel plot with Hedges' g values plotted against the standard error value of each effect (b).

In order to better characterize unisensory temporal processing deficits in DD, the auditory ($k = 8$), tactile ($k = 3$) and visual ($k = 8$) modalities were analysed separately. Large effect sizes were found for the auditory and visual modalities, indicating that a temporal processing deficit is present in DD in both modalities. Specifically, an effect size of $g = 0.87$ was found for auditory temporal processing (SE = 0.10; 95% CI [0.68, 1.06]; $p < .001$; Fig. 6a), and an effect size of $g = 0.78$ was found for visual temporal processing (SE = 0.17; 95% CI [0.45, 1.10]; $p < .001$; Fig. 6b). Tactile processing was associated with a moderate effect size of $g = 0.65$, which is to be interpreted cautiously due to the small size of this analysis ($k = 3$, SE = 0.15, 95% CI [0.36, 0.94]; $p < .001$). Impairments in the three modalities were not significantly different from one another when tested in a hierarchical meta-analysis model ($p = .642$).

Across 4 studies of multisensory temporal processing, a moderate effect size of $g = 0.53$ indicating impairment in DD was found (SE = 0.09; 95% CI [0.39, 0.67]; $p < .001$; Fig. 6c).

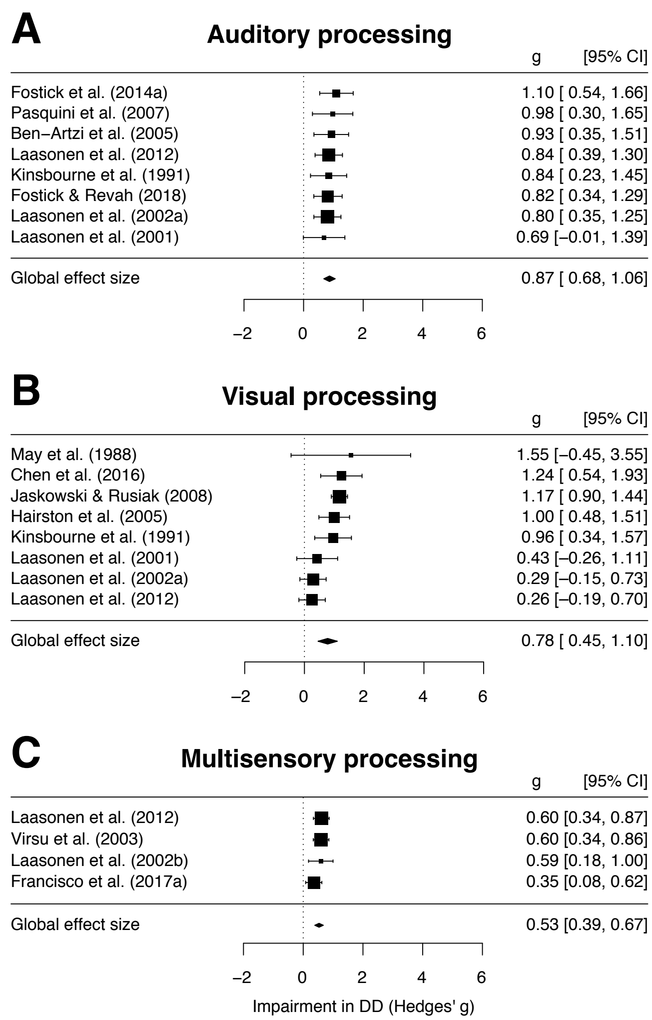

Fig.6. Forest plots showing study effect sizes and meta-analysis results for group comparisons of (a) auditory temporal processing, (b) visual temporal processing, and (c) multisensory temporal processing in DD.

3.4.3. Correlations with symptom severity in ASD

Only 3 studies measured correlations between temporal processing ability and symptom severity in ASD. The meta-analysis of their results yielded a non-significant overall correlation effect of r = -0.40 (k = 3; SE = 0.22; 95% CI [-0.84, 0.03]; p = .070). This effect was in the direction of more accurate temporal judgments corresponding with greater symptom severity.

3.4.4. Correlations with symptom severity in DD

In DD, a positive overall correlation of $r = 0.27$ was found between temporal processing and symptom severity (k = 5; SE = 0.10; 95% CI [0.08, 0.46]; p = .005). The direction of this effect indicates an association between impaired temporal processing and impaired reading skills in DD.

3.4.5. Effect of age in ASD

The examination of the moderating effect of age in ASD did not find an association between age and the degree of temporal deficits (k = 18; $B = -0.03$; SE = 0.02; 95% CI [-0.07, 0.01]; $p = .150$). Because this moderator analysis was performed upon effect sizes representing comparisons between ASD and TD, the result implies that impairment remains at the same level compared to the TD group through the age ranges included in the analysis (per-study mean ages of 10.3 to 30.7 years).

3.4.6. Effect of age in DD

Like ASD, an association between age and temporal processing impairment was not found in the moderator analysis in DD (k = 12; $B = -0.02$; SE = 0.01; 95% CI [-0.05, 0.01]; $p = .121$). This result suggests that impairment in DD is not greater in younger or older individuals. The range of study mean ages in this analysis was 9.0 to 36.5 years.

3.5. Heterogeneity among studies

Heterogeneity of effect sizes among studies was expected because of the use of different sensory modalities and stimulus types, as well as variation in sample demographics such as age and cognitive profile (Higgins and Green 2006; Higgins et al. 2003). In the analyses of overall group differences in temporal processing, there was a greater estimate of inter-study heterogeneity found for ASD (I^2 = 73.79%) than in the equivalent analysis in DD (I^2 = 56.28%). I^2 values of 50% are considered to indicate moderate heterogeneity, and 75% to indicate a high degree of heterogeneity (Higgins and Green, 2006).

In ASD, the multisensory analysis, comprised of a majority of audiovisual tasks, showed greater inter-study homogeneity (I^2=50.82%) than the unisensory analysis, which was comprised of tactile, visual, and auditory tasks (I^2=87.07%). In the analysis of tasks using speech stimuli, within-study variance was estimated to fully account for heterogeneity, yielding an I^2 estimate of 0%; this analysis may have been constrained by the limited number of studies (k = 6). The nonspeech analysis indicated a moderate to high level of inter-study heterogeneity (I^2= 62.96%).

In DD, the visual analysis yielded a moderate to high level of inter-study heterogeneity (I^2=65.23%), whereas for the auditory and multisensory analyses, I^2 was estimated at 0%.

In the analyses of correlations with symptom severity, the I^2 estimates were 78.65% in ASD, and 44.34% in DD. In the analyses of age effects on temporal processing, heterogeneity measures were I^2= 75.26% and I^2= 50.88%.

Notwithstanding the 0% estimates, most of these values indicate the presence of moderate to high heterogeneity as expected. This heterogeneity reinforces the necessity to conduct a random-effects meta-analyses to directly account for such variability (Borenstein et al. 2009; Higgins and Green 2006).

3.6. Publication bias

Publication bias was assessed in the overall analyses of temporal processing (ASD compared to TD; DD compared to TD) by means of visual inspection of symmetry in funnel plots in combination with Duval and Tweedie's trim and fill technique (Duval and Tweedie, 2000). No overt departures from symmetry are noted in the funnel plot for the ASD overall analysis; the corresponding trim and fill analysis resulted in one imputed value and the impairment effect remained significant with this additional value ($p < 0.001$; Fig. 3). The funnel plot for the DD overall analysis suggests a slight rightward asymmetry; the corresponding trim and fill analysis resulted in 6 imputed effect sizes and the impairment effect remained significant with these additional values ($p < 0.001$; Fig. 5). These trim and fill results do not suggest any strong publication biases affecting the present analyses.

4. Discussion

This is the first study examining temporal processing in both autism and dyslexia by means of systematic review and quantitative meta-analyses. Two widely-used temporal judgment tasks, SJ and TOJ tasks, were assessed in three different modalities (auditory, tactile, and visual), under unisensory and multisensory processing. A systematic review identified the main sample characteristics of ASD and DD studies as well as the types of tasks and modalities of interest. Several meta-analyses of temporal judgment tasks were conducted in order to establish the importance of temporal processing impairments in both disorders, as well as to assess potential associations of temporal processing ability with symptom severity (e.g., social communication for ASD, reading and writing for DD) and with age in each disorder. Results showed general impairments in both ASD and DD for overall temporal processing, as well as specific patterns of deficits associated with each disorder. In ASD, multisensory processing was moderately impaired, whereas unisensory processing showed no impairment compared to TD. When examining sensory modalities separately, both tactile and visual processing showed no impairment. Temporal judgments of speech stimuli showed a moderate impairment effect size whereas nonspeech stimuli showed a small effect. In DD, unisensory auditory and visual processing were both associated with large impairment effect sizes, unisensory tactile processing showed a moderate impairment effect size, and multisensory processing was associated with a moderate impairment effect. Symptom severity was found to be correlated with temporal processing in DD, indicating that greater precision of temporal judgments corresponds to increased reading skills. In ASD, the association with symptom severity, as measured by the ADOS or the SRS, was non-significant but was in the direction of greater temporal resolution (narrower TBW) with greater severity. Age did not moderate the impairments in temporal processing for either clinical population, suggesting that while both ASD and DD lag behind TD individuals in terms of temporal acuity, typical developmental trajectories of improving temporal precision during childhood and declining precision during adult years may be present in both disorders.

4.1. Qualitative review and quality assessment

The qualitative systematic review and quality assessment identified three main issues to note in the studies of temporal processing in ASD or DD, which will be discussed here: gender, comorbidity, and IQ. Additionally, differences in prevailing methodological approaches in ASD and DD are discussed in relation to theoretical models of perceptual abilities in these disorders.

For both ASD and DD, only half the studies in the current review's study sample stated that participant groups were matched on gender. There have been reports of differences in perceptual performance between genders during development in both TD and ASD, extending to both unisensory and multisensory tasks (Huyck and Wright, 2018; Ross et al., 2015). Any lack of matching on gender could confound the interpretation of group performance results. In the present meta-analysis, such an effect was observed for temporal processing in DD, in which the effect size increased from moderate to large when studies were not matched on gender. This highlights the importance of matching gender between groups in studies of DD. Additionally, the ASD and DD samples in this review were not broadly representative of gender ratios found for these disorders in the general population. Recent estimates find a male:female gender ratio between 3-4:1 in ASD (Loomes et al., 2017), whereas the present sample contained a greater ratio of almost 5:1 (83% male). This exacerbates an underrepresentation and lack of conclusive power for females with ASD. Indeed, this underrepresentation and the importance of studying girls and women with autism is highlighted in an increasing amount of research (see Pellicano et al., 2014; Shefcyk, 2015). Likewise, DD generally shows a 1.5-3:1 ratio of male:female (Rutter et al., 2004), whereas the present sample contained less than a 1:1 ratio (42% male). Bearing in mind challenges that accompany recruiting clinical populations in studies, an effort should be made to ensure the generalizability of the results, which is aided by having matched and representative samples.

Secondly, in the current review, about a third of the studies did not present any information about comorbid disorders in their samples, and the remaining studies either excluded comorbidities or reported having no participants with comorbid disorders. Given that co-occurring disorders are common in both ASD (attention deficit and hyperactivity disorder (ADHD), obsessive compulsive disorder (OCD), oppositional defiant disorder (ODD), anxiety, etc.) (Joshi et al., 2010; Mattila et al., 2010; van Steensel et al., 2011) and DD

(ADHD, developmental coordination disorder, speech sound disorder; Chaix et al., 2007; Kadesjö and Gillberg, 2001; Peterson et al., 2009), any lack of reporting of co-occurring disorders is problematic because presence of comorbidities might introduce confounds in the study results. Noting the presence of comorbidity can allow researchers to interpret results with caution. In particular, attention deficit and hyperactivity disorder (ADHD) is a neurodevelopmental disorder that commonly co-occurs with both ASD and DD (Antshel and Russo, 2019; Germanò et al., 2010), and can have an impact on the attentional capacities of individuals. Tasks measuring temporal processing typically are taxing and demand great attentional resources; for example, sustained attention predicted performance in auditory and visual TOJ tasks in a large sample of TD and literacy impaired children (Landerl and Willburger, 2010). This amplifies the need to measure and control for attentional deficits when assessing psychophysical tasks such as SJ and TOJ. Investigating potential differences between individuals with and without ADHD in ASD and DD could provide useful additional context to this question, because the impairment profiles of individuals with comorbid ADHD+ASD or ADHD+DD can extend beyond the combined diagnostic characteristics of the two diagnoses (Antshel and Russo, 2019; Germanò et al., 2010).

The quality assessment found the overall quality of studies in both populations to be satisfactory. However, one criterion that stood out as neglected in DD was the matching and reporting of IQ. Before 2013, a diagnosis of dyslexia required normal intellectual functioning (DSM-4; APA, 1994), so there may have been a presumption in these studies that confounds between IQ and clinical group were unlikely to arise. Nevertheless, there is still an important variation in the IQ of participants (TD or not) and IQ is known to play an important role in psychophysic tasks relating to perception, highlighting the importance to measure IQ and ensure matching in such studies (Acton and Schroeder, 2001; Helmbold et al., 2006).

The qualitative review identified differences and similarities in the ways that temporal processing is studied in ASD and DD. First, research in ASD focused on multisensory processing to a greater extent than in DD. DD studies were mostly oriented toward unisensory auditory and visual processing tasks, whereas less than a quarter of the studies measured multisensory temporal processing. In contrast, more than half of the ASD studies measured audiovisual temporal processing. These differences likely relate to the theories and past findings guiding the research. Key perceptual issues identified in ASD include difficulties in associating complex stimuli (Happé and Frith, 2006), impaired integration of sensory information (Brock et al., 2002), and potential enhancements in unisensory low-level processing (Mottron et al., 2006). In contrast, in DD most theories have focused on individual modalities rather than the integration of sensory information to explain deficits in reading and writing (Hahn et al., 2014). Although multisensory processing has gained more attention in DD in recent years, it is surprising to realize that only a handful of studies have assessed multisensory temporal processing in this population, given the multisensory nature of learning to read and write.

Task paradigms and outcome measures also showed differences in usage between ASD and DD. In ASD, the SJ and TOJ tasks had similar frequency of usage, and these tasks were generally used to estimate the TBW and perceptual thresholds respectively. In DD, the most common task was TOJ, and performance was measured in terms of a perceptual threshold or accuracy scores. It is important to note that different tasks and measures may vary in sensitivity in regards to measuring temporal processing. Future studies assessing how these methodological choices affect the degree of observed impairment could benefit our understanding of temporal processing in ASD and DD populations.

4.2. Temporal deficit profiles in ASD and DD

As expected, both disorders exhibited overall impairments in temporal processing. Different performance profiles were found in ASD and DD, where the size of the impairment effect varied depending on the sensory modality and type of stimuli. Although the pattern of results suggests greater overall temporal processing impairment in DD than in ASD, it is important to bear in mind that methodological differences between samples likely influence the pattern of results, such as the type of tasks and stimuli used.

The analysis of overall unisensory effects in ASD did not show clear impairment in unisensory processing. In examining individual studies, while studies using tactile and auditory tasks have reported either deficits or no difference (Ide et al., 2019; Kwakye et al., 2011; Puts et al., 2014; Tommerdahl et al., 2008; Wada et al., 2014), visual tasks effects have been reported in the direction of advantage for ASD (Falter et al., 2013), impairment (de Boer-Schellekens et al., 2013b; Kwakye et al., 2011), as well as no difference (Isaksson, 2018). Unisensory performance differences and their underlying causes in ASD may very well be modality dependent. As the modality specific analyses showed, visual temporal processing is not characterized by deficits. This is coherent with previous literature documenting visual processing strengths in ASD for static tasks (Bakroon and Lakshminarayanan, 2016) and visual search (Kaldy et al., 2016). Tactile temporal processing did not show any impairment, but showed more variability compared to the visual modality. The interpretation of unisensory temporal processing in ASD remains limited due to the few available studies. Unfortunately, not enough studies in the auditory modality were available for a quantitative analysis, so it is too early to state with certainty how auditory temporal processing may be impacted in ASD.

A finer look at the ASD analyses points to a moderate impairment in multisensory temporal processing, and a larger TBW for ASD compared to TD. Again, this means that for individuals with ASD, sensory information arriving from different modalities is integrated over a larger temporal interval compared to TD individuals; this is consistent with findings from the meta-analysis conducted by Zhou et al. (2018).

Several leading theories of ASD sensory perception (Brock, 2002; Happé and Frith, 2006; Mottron et al., 2006) highlight potential deficits when tasks require integration of multiple sources of information, and potential advantages in ASD for processing of simple, low-level information. While several of these theories are not specifically formed on temporal processing research, their extension to this domain might predict deficits in multisensory temporal processing, and preserved or superior acuity in unisensory processing. The present results confirm impaired multisensory temporal processing in ASD, but are less clear about the status of unisensory temporal judgments. However, a direct comparison did not find a difference in effect size between multisensory and unisensory tasks.

Considering multisensory and unisensory tasks together, deficits were found for both speech and nonspeech stimuli in ASD. Speech stimuli, such as syllables (e.g. Stevenson et al., 2014) and words (e.g. Regener, 2015), resulted in lower temporal processing performance compared to nonspeech stimuli (e.g., tools, flash and beeps, pure tones). Based on these findings, it is reasonable to hypothesize that temporal processing of speech information is more challenging for individuals with ASD. For example, it is interesting to note that Feldman et al. (2018) found that audiovisual integration of speech in ASD was more predictive of symptom severity compared to nonspeech stimuli. Further studies should investigate the extent to which temporal processing of speech is particularly impaired in ASD.

In DD, results are consistent with theories of temporal processing in DD (Stein and Walsh, 1997; Tallal, 1980) that predict impairments in auditory and visual processing, and suggest that these sensory deficits might also extend to tactile processing. As a group, DD shows deficits in auditory, tactile, and visual processing compared to TD. However, there is also evidence that temporal processing deficits are not present in all individuals with DD, and impairments in one modality do not necessarily co-occur with those in another modality (Landerl and Willburger, 2010; Ramus, 2003). The present meta-analysis also shows worse performance in DD compared to TD for multisensory tasks involving auditory, tactile, and visual modalities. Although few studies currently characterise multisensory temporal processing in DD, this finding is consistent with the idea that multisensory integration deficits may be causal to reading and writing problems in DD (Gullick and Booth, in press; Hahn et al., 2014).

The heterogeneity of DD as a group may warrant using different research methods than comparing DD and TD groups in search of differences. As mentioned earlier, although group differences in temporal processing are found in the present meta-analysis, only a portion of individuals with DD are typically found to have sensory processing impairments (Ramus, 2003; Calcus et al., 2016). Few studies of temporal processing in DD have made subtype distinctions within their samples. Fostick and Revah (2018) found that patterns of temporal deficits may interact with other abilities such as working memory to define groups within DD. Furthermore, Laasonen et al. (2012) clustered participants according to variables such as phonological awareness, rapid naming, reading speed and accuracy. They found that temporal processing affected DD severity in a way that cuts across subtypes (Laasonen et al., 2012). Clustering based on different deficits and characteristics has been useful in other disorders such as auditory processing disorders according to phonological awareness, attention, memory and language skills (Sharma et al., 2019). Future research may find this approach to be a promising avenue to understanding the sensory processing foundations of DD.

The majority of studies using speech stimuli in temporal judgment tasks in DD presented a methodological disparity that prevented their inclusion in these meta-analyses (SOA values > 100 ms; see section 2.1). For this reason, a comparison between temporal processing in speech and nonspeech was not possible for DD. However, two studies did examine speech stimuli in DD with comparable methodologies in the present analyses, and both these studies found impaired temporal judgments in the speech condition, suggesting that the general deficit in temporal processing found here in DD likely extends both to speech and nonspeech.

4.3. Clinical severity and temporal processing

Associations between symptom severity and temporal processing ability were expected for both ASD and DD. In ASD, only three studies were available to assess this question, and did not show a significant correlation. More studies are needed to investigate this potential association. Nonetheless, there is evidence from other studies that in some contexts, sensory integration does relate to symptom severity. A small to moderate association between common measures of ASD symptom severity (e.g., ADOS and SRS) and audiovisual multisensory processing was found in a recent meta-analysis (Feldman et al., 2018). Other studies have used more specific indices of severity. Ide et al. (2019) found that tactile temporal processing was associated with sensory hypersensivity, where better performance on a tactile TOJ task was associated with greater sensitivity to daily sensory experiences. Additionally, Noel et al. (2017a) investigated non-verbal interpersonal synchrony, as measured by body movement synchrony during spontaneous conversation, in relation to the multisensory TBW in ASD and TD participants. Results indicated that non-verbal interpersonal synchrony was related to the TBW in TD but not in ASD, such that individuals with ASD showed an uncoupling between sensory perception and interpersonal synchrony. Moreover, studies in the general population have found correlations between self-reported autistic traits and temporal processing (Donohue et al., 2012; van Laarhoven et al., 2019; Yaguchi and Hidaka, 2018). Some of these autistic traits show positive associations with temporal processing ability, whereas other aspects are negatively associated. For example, van Laarhoven et al. (2019) found that the presence of rigid and restricted behavior traits was associated with a larger TBW, whereas an attention to detail was associated with a narrower TBW. Given the mixed directions of these results, and bearing in mind the wide heterogeneity of the autism spectrum, relations between ASD clinical severity and temporal processing might be quite nuanced depending on the outcome measure examined.

In DD, the present analyses found a small but significant association between temporal processing and reading skills, where increased reading accuracy (fewer reading errors) was related to better temporal processing. This result agrees with varied evidence in the general population associating temporal processing and literacy skills across different reading levels. For example, Plourde et al. (2017) found that auditory and visual processing in school aged children, as measured by a TOJ task, was predictive of reading skills in a sample containing a continuum of participants from strong to impaired reading skills. Furthermore, in an undergraduate student sample, above-average readers were found to have better auditory TOJ performance than average readers (Au and Lovegrove, 2001). In children, a longitudinal study found grade one TOJ auditory processing to be predictive of grade two reading and spelling skills (Steinbrink et al., 2014). Another longitudinal study with children, by Vanvooren et al. (2017), measured temporal auditory processing with frequency modulation and rise time discrimination tasks. They found auditory processing deficits in kindergarten to impact the development of phonological awareness, which in turn predicted children's literacy skills in grade two. Auditory processing is said to be one of many contributors to phonological awareness and literacy skills, along with speech perception (Vanvooren et al., 2017). Examining SJ and TOJ tasks as well as the TBW in pre-reading individuals at risk of developing DD could similarly shed light on the development of phonological awareness and its dependence on temporal processing ability.

It is also important to keep in mind that the association between temporal processing and DD symptom severity might depend on the severity measure used. For example, there may be a different relation with reading accuracy than with reading speed. Additionally, there is likely an interaction between severity measure and the language involved. Italian and Spanish are examples of languages that have a high grapheme to phoneme correspondence, for which accuracy in DD readers is preserved but speed is impaired (Peterson and Pennington, 2012; Ziegler et al., 2003). As more research becomes available, especially from countries beyond the current sample, the relationships between literacy measure, language, and temporal processing profile may become better understood.

4.4. Developmental changes in temporal processing

For both ASD and DD, the level of temporal processing impairment was not associated with age. The results suggest that while temporal processing may follow similar developmental patterns in ASD and DD as in TD, i.e. improving in precision during childhood and gradually diminishing in precision during adulthood, the overall impairments identified here do not "catch up" to TD during development in ASD or DD.

Because of the available literature, developmental effects on temporal processing were examined here by testing for associations between age and temporal judgment impairment across studies (i.e., meta-regression). A more powerful approach to this question would involve studies that test for associations between temporal ability and age across individual participants. However, only three studies in the current review examined age effects on temporal judgments in DD, which was insufficient for quantitative meta-analysis. To our knowledge, no studies have investigated such age effects in ASD.

Several studies offer additional context for the present age results. In ASD, while the present results support the idea that affected individuals remain impaired in temporal processing in comparison to TD over the lifespan, there is some evidence from a broader range of multisensory integration studies (including temporal and non-temporal tasks) that integration performance differences between ASD and TD may diminish from childhood to adulthood (Beker et al., 2018; Feldman et al., 2018). In DD, three studies have examined age effects on temporal processing during adulthood (Hairston et al., 2005; Laasonen et al., 2002a; Virsu et al., 2003). Both unisensory and multisensory judgments became more impaired in DD relative to TD between ages 20 and 59, an age range that extends beyond the present analyses. Together, these results suggest that group differences between DD and TD may remain largely the same from childhood to adulthood, but then increase in subsequent decades of life.

In all, while the present results do not find a dependence of temporal processing deficits on age in ASD or DD, there are limitations that arise from the sensitivity of the meta-regression approach, which uses only the mean age from each study, as well as the number of studies available. It is clear that more studies are needed to investigate the influence of development on temporal judgments across the lifespan in both ASD and DD, and these may resolve differences in temporal processing at specific stages of development.

4.5. The role of temporal processing in ASD and DD

Although it is still unclear how temporal processing impacts ASD symptomatology, and what mechanisms are at play, it has been proposed that underlying temporal processing deficits may have a compounding or cascading effect upon higher order deficits in communication and social function. According to Stevenson et al. (2018), audiovisual temporal processing influences multisensory integration of social information, which in turn is predictive of speech perception abilities. They propose that temporal processing and sensory integration are important targets for clinical interventions, with the hope these will promote amelioration of social communication deficits (Baum et al., 2015; Wallace and Stevenson, 2014).

Similarly, there is a hypothesized causal link between temporal processing and reading/writing skills in dyslexia. As such, some interventions have been developed that target rapid auditory processing skills, based on the RAP theory (Tallal, 1980). One such intervention, Fast Forword®, is advertised as a language and reading intervention software targeting auditory processing, attention, and memory in school aged children (Scientific learning corporation, 1998). Unfortunately, there is little empirical evidence supporting the efficacy of this program, according to a systematic review and meta-analysis (Strong et al., 2011). Other interventions following a similar approach but focused solely on audiovisual training for reading remediation have yielded promising results (see Hahn et al., 2014 for a review).

In both disorders, the development of temporal acuity and sensory integration is yet to be understood in relation to the development of higher-order abilities. It might be that there is a critical or sensitive period during which temporal acuity is most influential in the development of these abilities. In this case, interventions targeting temporal processing should be tailored to help individuals reach their full potential before deficits in social communication or reading are fully developed.

4.6. Limitations

The present review was limited by several aspects of the available literature in ASD and DD. Firstly, the range of temporal perception tasks under review was intentionally narrow, which carried the advantages of increasing specificity and reducing heterogeneity across studies, but also constrained the number of studies available to review. Secondly, the prevailing of methodological approaches in the reviewed literature varied between ASD and DD, which limited the ability to quantitatively compare the degree of temporal processing impairment between these disorders. Moreover, some comparisons of interest were not feasible because of a lack of studies, such as the analyses of tactile processing in either disorder, speech stimuli in dyslexia, and individual unisensory modalities in ASD.

Several considerations also apply to the interpretation of the present results. The quality assessment found that some studies did not clearly demonstrate matching of groups on demographic characteristics such as gender and intellectual functioning, leaving open the possibility that some variation in temporal judgment performance is influenced by group differences on these characteristics. The analyses of age effects were constrained in sensitivity by the meta-regression approach, which tests for a relation with age across studies, but is not able to benefit from age variation within studies. Greater availability of studies that directly assess age correlations will permit more sensitive meta-analyses of developmental effects on temporal ability in the future. Finally, there are several considerations to bear in mind about generalizations to these two clinical populations. The available ASD studies were limited to participant samples having IQ in the unimpaired range, which limits any conclusions about the strength of temporal processing impairments in individuals at lower cognitive functioning levels. In DD, studies did not characterize individuals in their samples in terms of the type of DD (phonological, surface, mixed). The results are therefore presented for DD as a whole, but it is understood that more distinct profiles of temporal perception could emerge if subtypes of DD were described and compared.

4.7. Future directions

Sensory processing and multisensory integration are key aspects of ASD and DD. A clearer understanding of the role of temporal processing deficits in these disorders will help to refine clinical phenotypes and set a theoretical groundwork for future interventions to improve individual outcomes. In ASD, more research is needed to establish how unisensory temporal impairments may depend on the specific sensory modality. In DD, a greater research emphasis on multisensory processing will provide a clearer understanding of how sensory integration relates to reading and writing abilities. In particular, an investigation of the multisensory TBW in DD could provide a new conceptualization of temporal integration deficits in this population and provide a foundation to assess effects of interventions targeting multisensory integration. Furthermore, to understand developmental and clinical features of temporal processing, individual studies should measure the relations between variables such as age and clinical severity. Neuroimaging studies investigating temporal processing and neural activation could also help elucidate individual differences of task performance in TOJ and SJ. Current understanding of the importance of cortical and subcortical regions such as posterior temporal cortex, cerebellum, basal ganglia and insula for timing perception (e.g., Powers et al., 2012; Love et al., 2018) provides potential points of connection with brain atypicalities found in cerebellum and temporoparietal cortex in ASD (Igelström et al., 2017) and DD (Linkersdörfer et al., 2012). One theory in DD proposes that temporal processing deficits and consequent effects on reading ability may arise from impaired development of the visual magnocellular system, connecting from the retina to cortical visual processing areas, as well as similar large neurons present in the auditory system (Stein, 2019). Further research in ASD and DD targeted specifically at neural bases of atypical temporal processing will clearly benefit our understanding of these deficits.

A more detailed understanding of temporal processing profiles in ASD and DD opens the potential for interventions to ameliorate atypical temporal processing and promote improved outcomes in core symptoms (Bidelman, 2016; Stevenson et al., 2013). Interventions that emphasize temporal components, such as musical rhythm-based approaches, should be considered in relation to temporal processing and multisensory integration. Musical training has been shown to confer multisensory integration benefits, such as a narrower TBW (Lee and Noppeney, 2011) and greater temporal acuity in auditory tasks (Bishop-Liebler et al., 2014; Zuk et al., 2017). Several music intervention studies have shown promising results on key behavioral outcomes in both ASD (Thompson et al., 2014; Sharda et al., 2018) and DD (Flaugnacco et al., 2015; Habib et al., 2016), and future research can elucidate the roles that temporal processing may play in this improvement.

4.8. Conclusion

The present review finds general impairments in temporal processing for both ASD and DD, as measured by judgments of temporal order and simultaneity, as well as specific profiles of unisensory and multisensory impairments in each disorder. These findings help refine our understanding of sensory processing in ASD and DD and contribute to an evidence-based rationale for the development of new interventions and strategies aimed to ameliorate sensory functions and core symptoms in these disorders. Further studies are needed to more comprehensively describe the relations between temporal processing and symptom severity (i.e. social communication and restricted and stereotyped behaviors in ASD, reading and writing in DD) and the developmental trajectory of temporal processing in both disorders.

General discussion

The objective of this thesis was to assess temporal processing deficits in ASD and DD in order to refine these clinical phenotypes. This work has the potential to guide future investigations in temporal processing in ASD and DD by setting recommendations based on current qualitative and quantitative results. The investigation took the form of a systematic review and meta-analysis across studies between 1980 and 2019 that tested the SJ and TOJ paradigms in ASD or DD.

Overall, findings revealed that:

1. There is a general impairment in both ASD and DD for temporal processing including all modalities and types of tasks examined together (auditory, visual and tactile modalities; TOJ and SJ tasks).
2. There are patterns of deficits associated with each disorder. Multisensory processing was consistently impaired in ASD, and temporal judgments of speech stimuli were associated with impairment to a greater extent than nonspeech stimuli. In DD, auditory and visual processing were both associated with large impairment effect sizes, and multisensory processing with a moderate impairment effect. Tactile processing also showed a moderate impairment effect size, although this result should be interpreted with caution, as only three studies were included in the analysis.
3. Symptom severity was associated with temporal processing in DD, indicating that greater acuity corresponds to increased reading skills. In ASD, the association with symptom severity was non-significant but was in the direction of greater temporal acuity (narrower TBW) with greater symptom severity as measured by the ADOS or the SRS.

4. Age did not moderate the impairments in temporal processing for either clinical population, suggesting that while both ASD and DD lag behind TD individuals in terms of temporal acuity, typical developmental trajectories of improving temporal precision during childhood and declining precision during adult years may be present in both disorders.

Contribution of this master's thesis to research in sensory processing in ASD and DD

The overall aim of the current review was to better understand the clinical phenotypes of ASD and DD, taking a systematic and quantitative approach to provide an updated and quantitative account of temporal processing. As such, this is the first quantitative review to bring together two neurodevelopmental disorders in order to better understand temporal processing. The focus on two specific, commonly used temporal perception tasks helped to assess consistency and specificity across prior research, and provided a foundation to better understand patterns of deficits across unisensory processing, temporal binding and multisensory integration in ASD and DD.

First, these results bring an updated and nuanced understanding of temporal processing of auditory, tactile and visual modalities in ASD and DD. As expected, both disorders exhibited overall impairments in temporal processing. Different performance profiles were found in ASD and DD, where the size of the impairment effect varied depending on the sensory modality and type of stimuli. In ASD, impairments were found for multisensory sensory processing, nonspeech and speech processing. In DD, impairments were found for auditory, tactile and visual processing as well as for multisensory processing. Additionally, although the pattern of results may suggest greater overall temporal processing impairment in DD than in ASD, it is important to bear in mind that methodological differences between samples likely influence the pattern of results, such as the type of tasks and stimuli used. Taken together, these findings provide a characterisation of the type of temporal processing deficits in ASD and DD and established their magnitude in terms of effect size.

Second, these findings strengthen the need to pursue research of symptom severity in relation to temporal processing in DD, and set the stage for similar research in ASD. Although a significant association with severity was not found, the result showed a trend in the direction of increased temporal judgment performance with greater symptom severity. This finding goes against our hypothesis and other findings in ASD for multisensory integration (Feldman et al., 2018). A possible explanation for these results may be the heterogeneity of the analysis, with one multisensory study and two unisensory studies (visual and tactile), and the homogeneity of the sample (high functioning ASD). Specifically, it is possible that the association between symptom severity and temporal sensory processing varies according to modality. For example, it may be that visual acuity is generally greater in ASD compared to TD (see Falter et al., 2012), and is therefore associated with “more” ASD symptoms. Another possible explanation could be the varying type of severity outcome measure used in studies (social communication or restricted and repetitive behaviors; parent questionnaire or observational grids). Research correlating autism-related traits in the general population to temporal processing has found mixed results that partly support the present findings. In particular, some autistic traits show positive associations with temporal processing ability, whereas other aspects are negatively associated (e.g., van Laarhoven et al., 2019). Given the mixed directions of these results, and bearing in mind the wide heterogeneity of the autism spectrum, relations between ASD clinical severity and temporal processing might be quite nuanced depending on the outcome measures examined.

In DD, the present analyses found a small but significant association between temporal processing and reading skills, where increased reading accuracy (fewer reading errors) was related to better temporal processing. This result agrees with varied evidence in the general population associating temporal processing and literacy skills across different reading levels (Au and Lovegrove, 2001; Plourde et al., 2017; Steinbrink et al., 2014). Despite this evidence, how and if temporal processing contributes to phonological processing deficits is still unknown. Examining SJ and TOJ tasks in pre-reading individuals at risk of developing DD could shed light on the development of reading and writing and its dependence on temporal processing ability.

Third, these findings solidify current knowledge surrounding temporal processing and age in both disorders. For both ASD and DD, the level of temporal processing impairment was not associated with age. The results suggest that while temporal processing may follow similar developmental patterns in ASD and DD as in TD, i.e. improving in precision during childhood and gradually diminishing in precision during adulthood, the overall impairments identified here do not "catch up" to TD during development in ASD or DD. Because of the available literature, developmental effects on temporal processing were examined here by testing for associations between age and temporal judgment impairment across studies (i.e., meta-regression). A more powerful approach to this question would involve studies that test for associations between temporal ability and age across individual participants.

Recommendations

The systematic review and meta-analysis identified key aspects of the current literature in ASD and DD temporal processing that could benefit from the following recommendations. A first set of recommendations concerns the selection of participant samples: the matching and reporting of gender and IQ, and the inclusion of comorbid disorders. For both ASD and DD studies included in the present review, there was a lack of matching on gender, which can confound the interpretation of group performance results. Future studies should take great care to report the gender ratios of their sample but also to have gender ratios that are matched between groups. Concerning DD studies only, there was poor matching and reporting of IQ. Before 2013, a diagnosis of dyslexia required normal intellectual functioning (DSM-4; APA, 1994), so there may have been a presumption in these studies that confounds between IQ and clinical group were unlikely to arise. That being said, future studies should definitely report and match their groups on IQ, considering that IQ in the normal range can also vary considerably and may even influence performance on perceptual tasks. The diagnostic criteria for participant inclusion in DD also varied greatly. As some studies used professional referrals for determining the diagnostic, others evaluated performances in reading tasks (one standard deviation from the mean) to determine eligibility for DD participants. This variability in the inclusion criteria creates a lot of heterogeneity in the samples, which may not be representative of true DD individuals. Better inclusion criteria for DD in research must be developed in the future, and studies should use standardized tools when available.

Concerning comorbidity, a third of the studies did not present any information about comorbid disorders in their samples, and the remaining studies either excluded comorbidities or reported having no participants with comorbid disorders. Given that co-occurring disorders are common in both ASD (Joshi et al., 2010; Mattila et al., 2010; van Steensel et al., 2011) and DD (Chaix et al., 2007; Kadesjö and Gillberg, 2001; Peterson et al., 2009), any lack of reporting of co-occurring disorders is problematic because presence of comorbidities might introduce confounds in the study results. In particular, ADHD is a neurodevelopmental disorder that commonly co-occurs with both ASD and DD (Antshel and Russo, 2019; Germanò et al., 2010), and can have an impact on the attentional capacities of individuals. Tasks measuring temporal processing typically are taxing and demand great attentional resources; for example, sustained attention predicted performance in auditory and visual TOJ tasks in a large sample of TD and literacy impaired children (Landerl and Willburger, 2010). Similarly, tasks using multisensory stimuli may be more taxing compared to unisensory tasks, which may explain the poor multisensory performance in ASD, for example. This underlines the need to measure and control for covariables such as attentional capacities and executive functioning when assessing psychophysical tasks such as SJ and TOJ in clinical populations. Moreover, noting the presence of comorbidity can allow researchers to interpret results with caution. Bearing in mind challenges that accompany recruiting clinical populations in studies, an effort should be made to ensure the generalizability of the results, which is aided by reporting participant characteristics and having matched, representative samples.

Finally, the tendency for researchers in each field (ASD or DD) to study unisensory versus multisensory processing was unbalanced. Specifically, the ASD sample was dominated by studies of the TBW and multisensory integration, whereas the DD sample barely considered multisensory integration. In order to fully grasp the importance of temporal processing deficits in both disorders, it is important for future research to examine both unisensory and multisensory temporal processing. Additionally, few studies have investigated both types of temporal processing in the same participants, which could provide more statistical power (by taking into account individual variance) and understand individual portraits of sensory processing.

Future directions

Sensory processing and multisensory integration are key aspects of ASD and DD. A clearer understanding of the role of temporal processing deficits in these disorders will help to refine clinical phenotypes and set a theoretical groundwork for future interventions to improve individual outcomes. In ASD, more research is needed to establish how unisensory temporal impairments may depend on the specific sensory modality. In DD, a greater research emphasis on multisensory processing will provide a clearer understanding of how sensory integration relates to reading and writing abilities. Furthermore, to understand developmental and clinical features of temporal processing, individual studies should measure the relations between variables such as age and clinical severity.

A more detailed understanding of temporal processing profiles in ASD and DD opens the potential for interventions to ameliorate atypical temporal processing and promote improved outcomes in core symptoms (Bidelman, 2016; Stevenson et al., 2013). Interventions that emphasize temporal components, such as musical rhythm-based approaches, should be considered in relation to temporal processing and multisensory integration. That being said, understanding temporal processing profiles in both ASD and DD will require future studies to examine different components of temporal processing. Individuals with ASD and DD might present different profiles of deficits and abilities depending on the type of temporal competences that are being measured. For one, although individuals with ASD may show deficits in temporal processing of two discrete events (i.e. longer TBW), other types of temporal processing may be preserved. For example, Jamey et al. (2019) found ASD was associated with intact rhythmic skills. Contrary to what was found with ASD, rhythm-based tasks were associated with poor performances in DD (Boll-Avetisyan et al., 2020; Huss et al., 2011). Performance on rhythm tasks were also shown to be negatively associated with language ability and phonological awareness in non-clinical groups (Swaminathan and Schellenberg, 2019; Steinbrink et al., 2019). Furthermore, DD has also been shown to be associated with amusia, a neurodevelopmental disorder that impacts music processing (Couvignou et al., 2019). While ASD and DD may present different profiles of temporal impairments, each disorder may benefit from music interventions in their own way.

Although more research examining the specific outcomes of music intervention is needed, evidence is accumulating showing promising results in both ASD and DD. In ASD specifically, music intervention is seen as a possible means for improving diverse symptoms such as motor deficits, emotional, social and communication deficits, as well as attentional problems (Bharati et al., 2019; LaGasse and Hardy, 2013; Jazen and Thaut, 2018).

In DD, benefits from extensive musical training have been found in terms of auditory temporal processing. Two cross-sectional studies compared adult musicians with and without DD to participants with DD that did not have any musical training (Bishop-Liebler et al., 2014; Zuk et al., 2017). Although auditory processing was enhanced in the DD musician group, these individuals presented persistent impairments regarding reading skills and speech perception compared to the TD musician group. It seems that specializing in a musical instrument can confer benefits to temporal processing, but may not transfer to phonological and reading skills. Studies targeting literacy skills with melodic and rhythmic interventions have shown positive results in TD populations (Gordon et al., 2015) and DD populations as well (Habib et al., 2016; Rolka and Silverman, 2015). Notably, one randomized controlled trial with children diagnosed with DD between ages 8 and 11 has found benefits for rhythmic abilities on measures of phonological awareness and reading skills (Flaugnacco et al., 2015).

Overall, several music intervention studies have shown promising results on key behavioral outcomes in both ASD (Thompson et al., 2014; Sharda et al., 2018) and DD (Flaugnacco et al., 2015; Habib et al., 2016), and future research can elucidate the roles that temporal processing may play in this improvement.

Concluding remarks

The main goal of this master's thesis was to gain a better understanding of temporal processing deficits in ASD and DD, through the lens of a systematic review and meta-analysis. The present review found evidence for impaired temporal processing in ASD and DD, as measured by judgments of temporal order and simultaneity, as well as specific profiles of unisensory and multisensory impairments in each disorder. These findings help refine our understanding of sensory processing in ASD and DD and contribute to an evidence-based rationale for the development of new interventions and strategies aimed to ameliorate sensory functions and core symptoms in these disorders. Further studies are needed to more comprehensively describe the relations between temporal processing and symptom severity (i.e. social communication and restricted and stereotyped behaviors in ASD, reading and writing in DD) and the developmental trajectory of temporal processing in both disorders.

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