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# The Relation of Auditory Temporal Processing to Language Development and Other Cognitive Processes: Methodological and Conceptual Considerations

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# Abstract

Separate lines of research have demonstrated relations between auditory temporal processing and language ability and between information processing speed and intelligence. Because these processes have rarely been studied in the same sample, it is unclear how auditory temporal processing and information processing speed may operate together and how they may relate to cognitive functions including language. The overarching aim of this dissertation was to integrate these lines of research to better understand whether auditory temporal processing has a unique relation with language, or whether it relates more broadly to language and other cognitive functions as a part of global information processing speed. Study 1 examined auditory temporal processing, information processing speed, language ability, and intelligence in 4-6 year olds (*N*=47). Results revealed that auditory temporal processing and information processing speed correlated with age and with each other, but previously identified correlations with language and intelligence were not supported. Results raised questions about the auditory temporal processing measure used, thus Study 2 involved a mixed methodological scoping review to disentangle behavioural measures and constructs of auditory temporal processing in the extant literature. The review identified five categories of tasks that reportedly measure six auditory temporal processing constructs. Study 3 was planned as a pilot of three, child-friendly auditory temporal processing tasks that were designed and programmed based on Study 3 results, using a sample of adults and investigating the same relations as Study 1. Data collection was interrupted by Covid-19, thus Study 3 was written as a pre-registration and Study 4 involved a feasibility assessment for measuring auditory temporal processing online. Results revealed that measuring auditory temporal processing online shows promise, but must first be tested to ensure accuracy, precision, and quality of stimuli in the specific context of the tasks being used due to the potential impact on millisecond level timing. Although the direction of this dissertation took a step back to disentangle questions outside of the original overall aim, the collective results return the field to a place where the original questions may be investigated with better clarity about important considerations that need to be made moving forward.

## Keywords

Auditory Temporal Processing, Information Processing Speed, Inspection Time, Auditory Temporal Processing Measurement, Language Development.

# Summary for Lay Audience

The way in which we process the smallest pieces of incoming sound information that we hear (auditory temporal processing) may influence how easily children learn language. Previous research has shown that auditory temporal processing and language development may be related, but what remains unknown is whether language development is specifically related to processing sounds or to the speed of processing information in general. The goal of this dissertation was to investigate how language and intelligence relate to auditory temporal processing and information processing speed. Study 1 measured auditory temporal processing, overall processing speed, language ability, and intelligence in 47 4-6 year old children. Results revealed that auditory temporal processing and processing speed related to age and to each other, but were not related to language ability and intelligence as previously found. Study 2 reviewed the literature to clarify how auditory temporal processing is defined and measured, and found five categories of auditory temporal processing tasks that reportedly measure six specific types of auditory temporal processing. With this information, Study 3 involved the design and programming of three child-friendly auditory temporal processing tasks to investigate the same relations that were studied in Study 1. Because Study 3 was interrupted due to Covid-19, Study 4 reviewed the literature to examine the possibility of measuring auditory temporal processing online. Results revealed that measuring auditory temporal processing online may be possible, but must first be tested using the specific tasks to ensure timing is not impacted by factors such as computer hardware and software. Overall, this dissertation aimed to understand how the processing of sensory information relates to the development of language, and this remains the aim going forward with a deeper understanding about how auditory temporal processing is and can be measured.

# Co-Authorship Statement

The contents of this dissertation are my original work, however, the studies for this dissertation were designed and conducted under the supervision of Dr. Janis Oram Cardy. Dr. Cardy contributed to the design, analysis, interpretation and manuscript preparation of each chapter. Chapters 2, 3, and 5 of this dissertation are being prepared for submission to scientific journals. Chapter 2 was also conducted in collaboration with Dr. Andrew Johnson, who contributed to the analysis, interpretation, and manuscript preparation.

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# 1 Introduction

The speed and success with which children's brains process perceptual input have long been questions of interest for child language researchers. Some work has focused on the potential influence of auditory temporal processing, the way in which humans perceive and process incoming acoustic information over time, on language development and disorders. Other work has examined the notion of information processing more broadly, for example, how general speed of processing of all types of information (auditory temporal included) may influence language development and disorders. My research seeks to investigate the nuanced relation between these variables and determine whether the hypothesized relation between auditory temporal processing and language ability is unique or part of a more global relation between processing and cognitive abilities. Auditory temporal processing, measured behaviourally and neuro- or electrophysiologically, has been shown to relate to language ability and impairment (e.g., Benasich et al., 2006; Benasich & Tallal, 2002; Heim et al., 2011; McArthur & Bishop, 2004; Oram Cardy et al., 2005). The theory of generalized slowing (Kail, 1994) suggests that children with impaired language may process all information more slowly than their peers with typically developing language. Although these different types of processing have been investigated, they have rarely been studied together in the same sample, which makes it difficult to infer the ways in which auditory temporal processing and information processing speed may operate to process incoming sensory information and how they may relate to cognitive functions, including, but not limited to, language ability.

This dissertation aims to explore the measurement of auditory temporal processing and determine how auditory temporal processing relates not only to language ability, but also to information processing speed and intelligence. The ultimate goal is to better understand whether auditory temporal processing has a unique relation with language ability, or whether it relates more broadly to language and other cognitive functions as a part of more global processing speed measures. To this end, this chapter provides an overview of the extant literature relevant to auditory temporal processing and its relation to language in children, and a mostly separate body of literature on informational processing and its relation to cognition (intelligence) in children.

## Theoretical Underpinnings of Auditory Temporal Processing

Auditory temporal processing is the way in which incoming acoustic information is integrated over time. This is done by segmenting acoustic information into *percepts,* which ideally contain the entirety of the acoustic information occurring within each segment (Cowan, 1984). Features of the acoustic signal (e.g., loudness, pitch, amplitude modulation, frequency modulation, and temporal resolution) must be integrated into the percept with good resolution and background noise must be filtered out to create an auditory stimulus representation, a memory structure corresponding to the auditory percept (Bailey & Snowling, 2002; Näätänen & Winkler, 1999). Depending on the efficiency with which this segmentation occurs, the percepts created contain different amounts of acoustic information. The *temporal window of integration*, a sliding window, dictates how much acoustic information is processed into one percept (Näätänen, 1990). The acoustic information that falls into one sliding, temporal window has similar acoustic features, comes from the same approximate location, and is integrated into one auditory percept. Information occurring beyond the temporal window becomes part of the next auditory percept (Näätänen & Winkler, 1999; Wang et al., 2005; Winkler et al., 1998; Yabe et al., 1997). A small window of integration segments less acoustic information into one percept and therefore results in good acoustic resolution. A large window of integration segments more acoustic information into one percept, which leads to a percept with poorer resolution because more information is integrated into the single percept. There is a greater risk of information being lost when percepts are formed with a large window of integration because more information needs to be processed and there is a risk that it is not all integrated successfully (Näätänen & Winkler, 1999; Tallal, 2000). In adults, the temporal window of integration is estimated to be about 100-200 ms, based on studies measuring the interstimulus interval (ISI) between two tones required for an adult to fully perceive the features of both sounds (Foyle & Watson, 1984; Yabe et al., 1997, 1998). While the temporal window organizes incoming acoustic information, interference of information consolidation early within a window may be caused by information occurring in the latter part of the window (Näätänen & Winkler, 1999).

The efficiency with which acoustic information is processed and integrated has been shown to mature with age. Some researchers have used event-related potentials (ERPs) to investigate the integration of rapidly presented auditory information based on the length of the ISI between two tones. Using this approach, Fox et al. (2010) demonstrated that children required longer ISIs than adults (200 ms vs 25 ms) to show neural responses to both tones. When measured behaviourally, various tasks of auditory temporal processing demonstrate improved performance with increasing age in children aged 6-10 years (Yathiraj & Vanaja, 2015). In addition to improved performance with age, Moore et al. (2011) reported less variability in auditory temporal processing in 10-11 year olds than in 6-7 year olds. Maturation of auditory temporal processing extends into adulthood, as the length of the temporal window of integration has been found to be shorter in adults than in older children and younger children, and shorter in older children than younger children (Wang et al., 2005).

## The Measurement of Auditory Temporal Processing

Both behavioural and neurophysiological auditory temporal processing tasks aim to assess responses to acoustic stimuli to determine the success with which the stimuli are integrated and percepts are formed. Neurophysiological measurement techniques such as electroencephalography (EEG) (e.g., Benasich et al., 2006) and magnetoencephalography (MEG) (e.g., Oram Cardy et al., 2005) have been used to assess auditory temporal processing, often through passive paradigms, in which participants hear acoustic stimuli and their neural responses to the stimuli are analyzed. In these studies, the neural responses to rapidly presented acoustic stimuli can demonstrate responses to one or multiple stimuli and shed light onto whether these stimuli are integrated into one percept or processed as separate percepts. Results of this type of study can provide information about the time required between acoustic stimuli in order for participants to successfully integrate the acoustic information into percepts with good resolution and the loss of minimal information. The neurophysiological measurement of auditory temporal processing is beneficial because participants do not need to actively participate, so variables such as instruction comprehension, attention to a task, and motivation are less likely to impact the results, although other variables such as movement can interfere with data collection.

Studies assessing constructs of auditory processing speed behaviourally date back to the 1970s. Behavioural tasks of auditory temporal processing require active participation and often involve computerized tasks that require participants to make some decision about the acoustic stimuli with which they are presented, usually including some type of rapidly presented auditory stimuli. Task requirements include making judgments based on characteristics of acoustic stimuli such as temporal order, frequency, duration, gap detection, and masking (ASHA, 2005). The advantages of measuring auditory temporal processing behaviourally are that it is less expensive, more accessible to participants, and easier to administer (Jerger & Musiek, 2000), but difficulty understanding instructions can be a challenge, and performance may depend on other factors, such as attention (Protopapas, 2014).

## Auditory Temporal Processing and Language

*Developmental language disorder* (DLD) describes a difficulty in understanding and/or using language in the absence of a known biomedical condition such as brain injury, cerebral palsy, Down Syndrome, autism spectrum disorder (ASD), or intellectual disability (Bishop et al., 2017). Studies have historically referred to DLD as specific language impairment or developmental dysphasia but in line with international consensus for use of the term DLD, I will use DLD to describe this population throughout this dissertation. A diagnosis of DLD does not depend on nonverbal ability. Children can receive a diagnosis of DLD irrespective of whether or not there is a discrepancy between their language ability and their nonverbal intelligence. Research has shown that individuals with communication disorders, such as DLD, experience more risk to their well-being due to communication impairment, difficulties with relationships, and concern about academic achievement (Lyons & Roulstone, 2018). Academic achievement is an ongoing concern for individuals with DLD or early language impairment and research has shown that students with DLD demonstrate poorer academic outcomes across reading, language, and mathematics than their peers with typical development (Young et al., 2002).

Many possible causes of DLD have been investigated and, while there is no agreed upon single cause, it is likely that DLD results from some interaction of multiple factors. Variables such as genetics and heritability, environment, and neurological characteristics and functionality may combine to play a role in the development of DLD (Bishop et al., 2010; Bishop et al., 1995; Dale et al., 2003; Herbert et al., 2003; Hwang et al., 2006; Vernes et al., 2008). One particular area of interest in this dissertation, based on the auditory processing account of DLD, is the role that auditory processing may play in language development, and particularly, the role it may play in language development in DLD.

Spoken language develops in infancy through repeated exposure to the phonological, pragmatic, syntactic, prosodic, and semantic subtleties of the language(s) to which the infant is exposed (Bailey & Snowling, 2002; Kuhl et al., 1997; Tallal, 2000). Phonemes, the smallest units of meaningful sound, are produced as part of long strings of sounds, without natural boundaries, and are impacted by the surrounding phonemes (Bailey & Snowling, 2002; Liberman et al., 1967; Tallal, 2000). Due to these inconsistencies, infants must break down the acoustic information into consistent units that represent the phonemes of their language, which is facilitated by the temporal window of integration (Tallal, 2000). Based on the way in which the temporal window of integration operates, if infants are forming percepts of acoustic information as they are learning language, the information that is processed as percepts and the information that is lost in the creation of percepts are of vital importance. Infants whose temporal window of integration results in greater lost information about phonemes during processing may learn language more slowly or differently than infants whose temporal window of integration creates percepts with better resolution. According to the rapid auditory processing account of DLD, it is proposed that when individuals have difficulties processing brief, rapidly presented information, and therefore difficulties resolving rapid temporal cues in sound at the phoneme level, the result may be difficulty in phonemic awareness and literacy acquisition (Tallal, 1980, 2000, 2004). Temporal processing is especially important in speech perception for recognition of phonemes using their distinctive features and for identification of similar words (Dlouha et al., 2007).

This potential relation between auditory temporal processing and language development has often been studied in infants and children with and without DLD as well as in children with other differentiating conditions such as ASD, with mixed results. Early studies of auditory temporal processing involved the *Auditory Repetition Task*, which uses varying ISIs and asks participants to identify the order of two tones with different frequencies or whether two tones are the same or different (Tallal, 1980; Tallal & Piercy, 1973). These early studies found that children with DLD aged 6-9 years required longer ISIs between tones to accurately identify their order or determine whether they were the same or different. In another study using an Auditory Repetition task, Oram Cardy et al. (2010) measured auditory temporal processing in children with typical development, DLD, and attention deficit/hyperactivity disorder (ADHD). Although children with DLD showed impaired auditory temporal processing relative to children with typical development, children with ADHD who did not have co-occurring DLD showed a similar pattern in their auditory temporal processing performance, suggesting that difficulties in tasks of auditory temporal processing may not be unique to children with DLD.

This relation between auditory temporal processing and language development has also been studied and supported in infants. Using both an EEG paradigm and behavioural task to assess auditory temporal processing, infants with and without a family history of DLD have been shown to respond differently to the rapid presentation of auditory stimuli (Benasich et al., 2006; Benasich & Tallal, 2002). Using behavioural look-time paradigms, infants with a family history of DLD obtained a temporal processing threshold of ~145 ms while infants without a family history of DLD performed significantly better and only required ~70 ms to detect differences in acoustic stimuli. In a passive EEG paradigm, infants with a family history of DLD responded to the second tone in a deviant tone pair with reduced amplitude in certain areas of the brain when compared to infants without a family history of DLD (Benasich et al., 2006). In other EEG studies with children, all children, with and without DLD, demonstrated a neural response to the first tone in a tone pair, but when tones were presented with ISIs of less than 150 ms, children with DLD showed fewer, smaller, or deviant responses to the second tone, which may indicate an impairment in auditory temporal processing (Heim et al., 2011; Oram Cardy et al., 2005).

Other studies have failed to find differences in auditory temporal processing in children with and without DLD or found differences inconsistently (e.g., Bishop et al., 1999; Nickisch & Massinger, 2009; Smyth et al., 2014). Bishop and colleagues (1999) observed individual differences in the performance of 8-10 year old children on backward masking and pitch discrimination tasks, but no group differences were observed.

Nickisch and Massinger (2009) found that children with DLD experienced deficits in tasks of frequency discrimination, but not in tasks such as gaps in noise or temporal order judgment that measure specific time processing skills. McArthur and Hogben (2001) used a *Backward Masking* task to measure auditory temporal processing in children with typical development, DLD with concomitant reading difficulties, DLD without concomitant reading difficulties, and reading disability without DLD. In their study, some children with DLD and a concomitant reading difficulty demonstrated impaired performance relative to the control group, but the remainder of the children with DLD and a concomitant reading difficulty performed as well on the *Backward Masking* task as the control group (McArthur & Hogben, 2001). Finally, Smyth et al. (2014) found no group differences on an Auditory Repetition task in children with and without DLD, although they did find a significant overall correlation between language ability and auditory temporal processing ability.

This overview of studies highlights the mixed support for the relation between auditory temporal processing and language ability in children. Recently, Magimairaj and Nagaraj (2018) proposed a framework to conceptualize children's listening difficulties and the ways in which auditory processing, language processing, and cognition relate to and influence these listening difficulties. Although this framework does not consider the ways in which auditory processing may impact language processing specifically, it does highlight the importance of considering cognitive factors in interpreting performance on tasks of auditory temporal processing (see Magimairaj & Nagaraj, 2018, Figure 3 for additional details). In Magimairaj and Nagaraj's framework, auditory processing is proposed to relate to and interact with other cognitive factors such as working memory and attention. Protopapas (2014) highlights additional task demands such as auditory memory and verbal processes that must be considered when measuring auditory temporal processing. He also emphasizes the potential impact that training (as studied by Heath & Hogben, 2004) can have on abilities such as attention to task, identifying the acoustic feature of interest, and tracking changes in that acoustic feature through an adaptive staircase paradigm, may have on auditory temporal processing performance (Protopapas, 2014).

## Information Processing Speed

*Information processing speed*, a global construct of processing speed that provides an overall measure of thinking, reasoning, and remembering, is the time required to perceive and make a decision about incoming sensory information (Coyle et al., 2011; Kail, 2000). Much like auditory temporal processing, information processing speed matures with age. Kail (1991) used response time to compare the slowing coefficient of children with typical development across 11 age bands and found that the slowing coefficient decreased (children responded faster) with increasing age. One measure that is thought to provide a particularly useful estimate of information processing speed is *inspection time* (IT), the shortest time a stimulus needs to be presented in order for a participant to make a judgment about it to a specific level of accuracy (Vickers et al., 1972). In the classic IT task, participants observe a figure with two vertical lines, one of which is longer. A mask appears to cover both lines and participants must determine which line was longer. The participant’s individual IT reflects the short presentation duration (before the mask appears) at which they can accurately identify the longer line. IT is most often measured using visual IT tasks but can also be measured using auditory IT tasks. It is important to note that auditory IT tasks do resemble certain measures of auditory temporal processing. While auditory IT tasks can vary, they do use a variation of a pitch discrimination task that involves some type of auditory mask (Deary, 1995).

# Information Processing Speed and Cognitive Processes

## Information Processing Speed and Intelligence

Information processing speed has been shown to act as a mediator of general intelligence (*g*) (Carroll, 1991; Coyle et al., 2011; Kranzler & Jensen, 1991). Despite factor analyses suggesting different conclusions about the nature of psychometric *g* as either a unitary process or composed of multiple independent processes, each study supports the hypothesis that information processing speed contributes to *g* (Carroll, 1991; Kranzler & Jensen, 1991). Park and colleagues (2015) investigated, specifically, the utility of linguistic and non-linguistic processing speed tasks (from Miller et al., 2001) in predicting intelligence in children with and without DLD. When nonverbal intelligence tasks that included a speed bonus were used, non-linguistic processing speed predicted nonverbal intelligence in children in grade 3 and grade 8 with and without DLD, suggesting that processing speed may not predict all aspects of nonverbal intelligence, but more specifically, nonverbal intelligence that is estimated using timed tests (Park et al., 2015).

Stemming from research into information processing speed and intelligence, a relation has also been established between IT, as a measure of information processing speed, and intelligence (Brand & Deary, 1982; Burns & Nettelbeck, 2003; Deary et al., 1989; Grudnik & Kranzler, 2001; Nettelbeck & Young, 1989, 1990; Sheppard & Vernon, 2008). Meta-analyses have identified correlations between IT (both visual and auditory) and intelligence in the range of about *r* = -.30, with correlations up to about *r* = -.58 when corrected for the effects of artifacts such as sampling error, attenuation, and range variation (Grudnik & Kranzler, 2001; Sheppard & Vernon, 2008).

As described above, the ways in which auditory IT is measured resemble certain types of auditory temporal processing tasks. While not all auditory IT tasks are the same, they originally employed a frequency discrimination component with an auditory mask (e.g., Deary, 1995), although tasks measuring auditory IT through the use of loudness and spatial judgments have also been developed (e.g., McCrory & Cooper, 2005; Olsson et al., 1998; Parker et al., 1999). To obtain an auditory IT threshold, participants hear two different tones as part of a tone pair that change in duration according to an adaptive procedure. Performance on auditory IT tasks has been shown to relate to performance on tasks of verbal and nonverbal intelligence (e.g., Brand & Deary, 1982; Deary, 1995; McCrory & Cooper, 2005; Parker et al., 1999), albeit correlations range based on the distribution in intelligence scores of the sample. When the sample includes a range of intelligence scores, the correlation between IT and intelligence is higher, whereas when the sample includes only those with average to above average intelligence, correlations are lower (e.g., Deary et al., 1989). The similarities between the measurement of auditory IT and auditory temporal processing may be reflected in how these constructs are related to cognitive abilities and may offer insight into the ways in which information processing speed and auditory temporal processing might be related.

### Information Processing Speed and Language

According to the theory of generalized slowing, or the processing speed account of DLD (e.g., Kail, 1994; Miller, 2014), processing speed, more generally, may account for the difficulties seen in language development in DLD. As has been previously described, generally, children with DLD have longer temporal windows of integration. Miller and colleagues (2001) found support for Kail's (1994) theory of generalized slowing in children with DLD. Children with DLD performed more slowly than typically developing children on a series of linguistic and non-linguistic reaction time tasks, but more quickly than children who had both impaired language and nonverbal intelligence that was below average (Miller et al., 2001). Park et al. (2015) used the same linguistic and non-linguistic tasks to determine the utility of linguistic and non-linguistic processing speed tasks in marking language impairment. The tasks identified as most useful (i.e., grammaticality judgment, simple response time, rhyme judgment) were more effective at identifying the presence of DLD as opposed to its absence. While the results from this study provided only a preliminary analysis of the diagnostic effectiveness of processing speed tasks for DLD, they supported the hypothesis that slower processing speed may help identify language impairment in adolescents with DLD (Park et al., 2015).

## Objectives and Overview

The relations between these different constructs of processing have been well studied and established across separate bodies of research. One body of research focuses on the relation between auditory temporal processing and language development and the other on the relation between information processing speed and cognitive abilities. As Miller (2014) explains, research comparing hypotheses of auditory processing and processing speed has been rare. While these processes have been studied separately, there are many links across these bodies of research, namely, the way in which different types of processing speed relate to different cognitive factors, and the use of various types of processing speed measures in determining the ways in which they relate to cognitive factors. To better understand these links, studies must begin to intentionally combine what is known based on each body of literature and investigate these relations together. The overarching aim of this dissertation is to examine how auditory temporal processing and information processing speed relate to each other and with other cognitive processes, namely language ability and intelligence, in an effort to determine whether these relations exist as part of one domain general process or separately as domain specific processes.

Chapter 2 describes an experimental study that sought to investigate these relations in a sample of 4-6 year old children. Using tasks of auditory temporal processing, information processing speed, language ability, and intelligence, I investigated how these processes relate to one another, focusing particularly on the question of whether auditory temporal processing and language ability are related as part of a domain specific relation or as a domain general process that exists between processing speed and cognitive abilities more generally.

The results of Chapter 2 were much less straightforward than anticipated, including a failure to find previously documented relations between auditory temporal processing and language, and between IT and intelligence. As a result, the remainder of the dissertation takes a step back and attempts to tease apart some of the questions raised by the pursuit of the original question. The results outlined in Chapter 2 highlighted a lack of clarity about the construct being measured by the auditory temporal processing task, so Chapter 3 sought to define, describe, and organize constructs of auditory temporal processing and determine how they are measured behaviourally. This was addressed through a qualitative methodological scoping review, employing principles of qualitative meta-synthesis, that investigated the behavioural measurement of auditory temporal processing across disciplines from 2014-2019.

The results of Chapter 3 informed the development of three behavioural auditory temporal processing tasks that were designed based on the results of the scoping review. Although designed for use with young children, the aim of the study described in Chapter 4 was to first use these tasks in adults to investigate the relations between how auditory temporal processing is measured in three different ways, how these three measures of auditory processing are related to information processing speed (as measured using IT), and how these processing measures relate to cognitive abilities such as language ability and intelligence. As a result of COVID-19, sufficient data collection could not be completed. Therefore, Chapter 4 was written as a pre-registration of the planned study. Also in response to COVID-19, Chapter 5 explores the literature on the feasibility of collecting behavioural data using an online format and considers the specific feasibility of testing auditory temporal processing online. Finally, Chapter 6 summarizes the findings of the four studies, considers their implications for the measurement of auditory temporal processing, and explores how they inform future directions for research into auditory temporal processing, information processing speed, and their relation to other cognitive factors.

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# 2 Language Development and Processing Speed in Young Children: A Domain General or Domain Specific Relation?

## Introduction

Auditory temporal processing requires individuals to process rapidly presented or briefly occurring acoustic information over time (Hartley et al., 2003; Ribeiro et al., 2015). *Auditory Temporal Integration* (ATI), one construct within temporal processing, entails integrating rapidly presented auditory information to create auditory percepts (the sounds that we perceive) by chunking incoming acoustic information into units across time (Cowan, 1984; Fox et al., 2010; Näätänen & Winkler, 1999). The ability to process acoustic information more quickly facilitates successful integration and provides a signal with higher resolution (Näätänen & Winkler, 1999), which has been proposed to support early spoken language development (Tallal, 2000). While ATI is specific to the auditory system, a global mechanism of processing incoming sensory information plays a role in most types of tasks (Kail, 2000). *Information processing speed* is the time that is required to perceive, receive, and interpret incoming sensory information, and then make a decision about it. It includes multiple processing systems and is thought to provide an overall index of thinking, reasoning, and remembering (Coyle et al., 2011; Julesz & Hirsh, 1978; Kail, 2000). One specific measure of information processing speed, *Inspection Time* (IT) is thought to reflect the fastest speed at which information can be processed (Vickers et al., 1972). ATI, and information processing speed more broadly, may function as part of one domain general system that supports overall cognitive functioning, and therefore general cognitive abilities (e.g., intelligence). Alternatively, they may relate to specific cognitive abilities, such as language, in domain specific ways.

The current study sought to investigate ways in which ATI and information processing speed are related to cognitive abilities, namely language development and intelligence, in children. Previous work has suggested that ATI and its relation to language abilities may be domain general and a function of overall processing speed. Alternatively, language abilities may be related to ATI in a domain specific way, independent from global processing speed.

Although individual studies have provided support for relations between (a) ATI and language ability (e.g., Benasich & Tallal, 2002; Bishop & McArthur, 2005; Oram Cardy, Flagg, Roberts, Brian, & Roberts, 2005), (b) information processing speed and language ability (e.g., Miller et al., 2001), and (c) information processing speed and intelligence (e.g., Brand & Deary, 1982; Nettelbeck & Young, 1989; Sheppard & Vernon, 2008) in children, a number of issues remain. First, some studies have failed to find these relations or have identified confounding variables that make it difficult to interpret these relations (e.g., Bishop, Carlyon, Deeks, & Bishop, 1999; Kwok, 2013; McArthur & Hogben, 2001; Nettelbeck & Young, 1990; Oram Cardy, Tannock, Johnson, & Johnson, 2010). It is possible that inconsistent support for the proposed relations across studies may in part relate to differences in how ATI, information processing speed, and cognitive abilities mature, and the possibility that relations between them may vary at different points in development. Measurement confounds, such as motor ability and reaction time, may also impact performance on (auditory and information) processing speed measures and may account for differences in processing speed performance between studies. Second, the age of participants has varied greatly across studies, with samples ranging from infants (6 months, Benasich et al., 2006) to adolescents (up to 15 years, Park, Mainela-Arnold, & Miller, 2015). Of key importance here, no study to date has evaluated ATI, information processing speed, language, and intelligence in the same sample of children, which has thus far limited our ability to consider the question of domain specific vs general relations to cross-study comparisons with variable samples and findings. The present study sought to address this issue.

## Objectives

The purpose of our study was to investigate whether the relations previously identified between ATI, information processing speed, language, and intelligence in children are best understood as part of one, domain general processing system or separately as domain specific processes. We were specifically interested in investigating these relations in children aged 4-6 for a number of reasons. First, the Benny Bee Inspection Time (IT) Task, which we used as our measure of information processing speed (which is described in more detail in the Method section) has been validated as a measure of IT and shown to relate to *performance intelligence* (PIQ) in addition to *verbal intelligence* (VIQ) and *full scale intelligence* (FSIQ) in children aged 4 (Williams et al., 2009). This was important because we hoped to reduce the potential confounds of language on IQ by measuring PIQ as opposed to VIQ. Additionally, because IT has been shown to relate to intelligence, both PIQ and VIQ, in children aged 6 (Nettelbeck & Young, 1989), we sought to assess the use of the Benny Bee IT Task in slightly older children in whom we would expect to see a relation between IT and PIQ. While relations between ATI and language ability have been supported in infants through look-time paradigms (e.g., Benasich & Tallal, 2002) and in school-aged children and adolescents (e.g., Bishop & McArthur, 2005; Oram Cardy et al., 2005), studies investigating this relation have been scarce in children younger than 7. This may be partially because the challenging nature of behavioural tasks traditionally used to measure ATI (ASHA, 2005). The tasks used in this study were designed for young children, and as such, we aimed to investigate the relations between ATI, information processing speed, language and intelligence in children aged 4-6.

We had four specific aims: a) to investigate the relation between language ability and ATI; b) to investigate the relation between intelligence and information processing speed; c) to investigate the relation between ATI and information processing speed; and d) to investigate the relations between age and each of ATI and information processing speed in young children. Based on previous research, we hypothesized that relations would exist between language ability and ATI and between intelligence and information processing speed. Based on the ATI theory of language development, we hypothesized that ATI would not be related to information processing speed. Under the ATI theory of language development, difficulties specific to auditory temporal processing, rather than global processing abilities, are a key contributor to language difficulties. Alternatively, under a domain general model, the *generalized slowing hypothesis* (Kail, 1994), relations may exist between ATI and information processing speed, indicating that auditory temporal processes may be but one index of overall processing speed and that relations between ATI and language ability reflect the influence of overall, domain general information processing.

# Method

## Participants

47 children (22 females) between the ages of 4 and 6 participated in this study (*M* = 5.88 years, *SD* = 0.49, Range: 4.67-6.92). They were recruited from an epidemiological sample of students who had participated in a previous language screening study in London, Ontario kindergarten classes and parents indicated they were willing to be contacted about future studies. Five additional participants were excluded because they did not speak English as a first language and two additional participants were excluded because they did not have full datasets due to equipment malfunction. All 47 participants in the final sample spoke English as their primary language and had no neurological, hearing, or uncorrected visual impairments.

## Measures

Participants completed a battery of tests assessing language ability, intelligence, ATI, and information processing speed.

### Language Ability

Language ability was assessed using two standardized tests. The *Peabody Picture Vocabulary Test-4$^{th}$ Edition* (PPVT-4), in which participants hear a word and select a picture that shows that word, was used as a measure of receptive vocabulary (Dunn & Dunn, 2007). The *Clinical Evaluation of Language Fundamentals-Preschool 2* (CELF-P2) Core Language Score (CLS), consisting of Sentence Structure, Word Structure, and Expressive Vocabulary subtests, was used as an overall measure of oral language ability (Wiig et al., 2004). The Sentence Structure subtest is a measure of receptive language structure that requires participants to select the picture that matches a spoken phrase.

Word Structure is an expressive language structure subtest in which participants must complete sentences assessing various grammatical markers. Finally, the Expressive Vocabulary subtest asks participants to label a word based on a picture, measuring expressive vocabulary (Wiig et al., 2004). By using these two measures of language ability, each of receptive and expressive, language structure and vocabulary were measured.

### Intelligence

Intelligence was measured using the PIQ score from the *Wechsler Preschool and Primary Scale of Intelligence-3rd Edition* (WPPSI, Wechsler, 2002). The tasks that make up the PIQ score are Block Design, Matrix Reasoning, and Picture Concepts. PIQ was chosen as opposed to FSIQ or VIQ because our interest in language ability led us to choose a measure of IQ that would be least confounded by language ability (DeThorne & Schaefer, 2004). Although studies investigating the relation between information processing speed and intelligence have often used FSIQ to measure intelligence, PIQ and informationa processing speed have also been shown to correlate in young children (Nettelbeck & Young, 1989).

### ATI

ATI was estimated using the Bird Task, a 4-interval, 2-alternative forced choice (4I-2AFC) computerized behavioural task. In this type of ATI paradigm, each trial consists of four tones presented in pairs and participants must decide which tone pair is separated by a longer gap. In the Bird Task, participants listened to two birds that, in every trial, chirped twice each. One, randomly varied bird always chirped with a gap of 0 ms between chirps, whereas the other bird chirped with a varying gap, ranging between 0 ms and 500 ms. Participants identified which bird chirped “the slowest,” that is, with the longer gap between chirps. The examiner selected the bird on behalf of the child to reduce motor confounds. The gap size of the varying bird was adjusted based on the accuracy of previous trials using a virulent parameter estimation by sequential testing (PEST) protocol (Findlay, 1978). A threshold of ATI was generated by the Bird Task, which was the threshold in ms at which the participant identified the bird with the longer gap between tones with 75% accuracy. Participants were given unlimited time to respond to ensure reaction time was not a confound.

## Information Processing Speed

IT, described as, “the time required by a subject to make a single observation or inspection of the sensory input on which a discrimination of relative magnitude is based” (Vickers & Smith, 1986, p. 609) was measured using the Benny Bee IT Task, which assesses IT using a pattern backward masking paradigm (Williams et al., 2009). Participants observed two identical flowers and were told that Benny is the fastest bee in the world. Benny appeared on one of the flowers and was quickly covered by seven bumblebees, which appeared on both flowers as a mask of the initial stimulus. Participants were asked to identify which flower Benny landed on before the mask appeared. The time between Benny appearing on the flowers and the mask changes, depending on the accuracy of previous trials. The Benny Bee IT task uses an adaptive staircase algorithm to produce an IT threshold, which is the threshold in ms at which the participant identifies the flower that Benny landed on with 79% accuracy (Williams et al., 2009). One strength of the Benny Bee IT Task in measuring IT in young children is that it assesses information processing speed but is not confounded by reaction time or motor function. Performance depends on the time required to make an observation about the stimuli, that is, the time it takes to respond does not impact performance.

# Results

Means, *SD*s, and ranges for age, language abilities, PIQ, IT threshold, and ATI threshold are provided in Table 2.1.

**Table 2.1 Mean, Standard Deviation and Ranges of Sample**

| Variable | Mean | SD | Range |
|---|---|---|---|
| Age | 5.88 | 0.49 | 4.67-6.92 |
| *PPVT* Standard Score | 113.31 | 10.98 | 88-136 |
| *CELF-P2* Sentence Structure | 10.89 | 2.92 | 5-15 |
| *CELF-P2* Word Structure | 10.51 | 2.46 | 5-15 |
| *CELF-P2* Expressive Vocabulary | 10.38 | 2.10 | 6-15 |
| *CELF-P2* Core Language Score | 103.02 | 11.39 | 83-123 |
| PIQ | 105.54 | 14.62 | 70-135 |
| ATI Threshold | 141.64 | 133.23 | 4-451 |
| IT Threshold | 189.39 | 109.40 | 51.45-566.94 |

*Note.* Peabody Picture Vocabulary Test (PPVT), Clinical Evaluation of Language Fundamentals (CELF) and Performance IQ (PIQ) are standard scores with $M = 100$ and $SD = 15$.

## Correlations

Pearson's product moment correlations were calculated between the experimental computer task variables and the norm-referenced test variables. A full summary of the correlations is presented in Table 2.2. Significant correlations were found between age and both measures of processing speed (ATI: $r = -.30, p < .05$; IT: $r = -.62, p < .01$). ATI threshold was correlated with one measure of language ability (*PPVT-4*: $r = -.45, p < .01$). IT threshold was not significantly correlated with PIQ ($r = -.27$). The measures of processing speed were significantly correlated with each other (ATI and IT: $r = .34, p < .05$). Of note, although ATI was not significantly correlated with the *CELF-P2* CLS, ATI did correlate significantly with the *PPVT-4* and the *CELF-P2* Sentence Structure subtest.

These two measures assess vocabulary and language structure receptively, whereas, the *CELF-P2* CLS encompasses one receptive language and two expressive language subtests.

**Table 2.2 Bivariate Correlations Between Experimental Measures and Psychometric Measures**

| | ATI Threshold | IT Threshold |
|---|---|---|
| Age | -.30* | -.59** |
| PPVT Standard Score | -.45** | -.20 |
| CELF-P2 Sentence Structure | -.38* | -.25 |
| CELF-P2 Word Structure | -.17 | -.09 |
| CELF-P2 Expressive Vocabulary | -.10 | -.15 |
| CELF-P2 Core Language Score | -.26 | -.23 |
| PIQ | -.28 | -.27 |
| IT Threshold | .34* | - |

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

## Regression

Direct-entry regressions were run on ATI and IT thresholds. The predictors included in the model for ATI threshold were age, *CELF-P2* CLS, *PPVT-4* and *WPPSI-III* PIQ (see Table 2.3). The model explained a significant amount of variance in ATI threshold, $R^2 = .14$, $F(4, 39) = 2.78$, $p < .05$, but there were no significant individual predictors, although age and *PPVT-4* were approaching significance. The predictors in the model for IT threshold were age, *WPPSI-III* PIQ, and *CELF-P2* CLS. Due to a violation of assumptions, one outlier was removed from this regression. The model explained a significant proportion of the variance in IT threshold, $R^2 = .41$, $F(3, 40) = 11.04$, $p < .01$. In this model, age significantly predicted variance in IT threshold, $\beta = -.56$, $t(40) = -4.35$, $p < .01$, but other variables did not (see Table 2.4).

**Table 2.3 Summary of Coefficients, Standard Error, t-values, and p-values for ATI**

| Predictors of ATI | B | B SE | *β* | *t* | *p* |
|---|---|---|---|---|---|
| Age | -74.38 | 40.41 | -0.28 | -1.84 | 0.07 |
| *CELF-P2* CLS | 1.32 | 2.54 | 0.11 | 0.52 | 0.61 |
| *PPVT-4* | -4.22 | 2.36 | -0.34 | -1.79 | 0.08 |
| *WPPSI-III* PIQ | -0.53 | 1.69 | -0.06 | -0.32 | 0.75 |

*Note*. Model accounts for 14% of the variability in ATI; $p < .05$; CI = confidence interval; * = significant variable; ATI = Auditory Temporal Integration; IT = Inspection Time.

**Table 2.4 Summary of Coefficients, Standard Error, t-values, and p-values for IT**

| Predictors of IT | B | B SE | *β* | *t* | *p* |
|---|---|---|---|---|---|
| Age | -117.72 | 27.04 | -0.55 | -4.35 | 9.05e-05* |
| *WPPSI-III* PIQ | -2.07 | 1.14 | -0.27 | -1.83 | .08 |
| *CELF-P2* CLS | 0.48 | 1.41 | 0.05 | 0.34 | .73 |

*Note*. Model accounts for 41% of the variability in IT, $p < .01$; CI = confidence interval; * = significant variable, $p < .05$; IT = Inspection Time; ATI = Auditory Temporal Integration.

## Post-Hoc Analyses

After reviewing the correlations, of particular interest were the various significant correlations with age. Despite being standardized, language scores (*CELF-P2* CLS and *PPVT-4*) were related to age. Two hierarchical regressions were run post-hoc to further investigate these observations, the first on ATI and the second on IT. Age was entered into both hierarchical regressions as the first predictor. In the regression explaining variance in ATI threshold, the variance accounted for beyond that of age was not significant ($p = 0.4$). In the regression explaining variance in IT threshold, once the variance accounted for by age was removed, other variables did not significantly predict any additional variance ($p = 0.3$).

# Discussion

This study sought to investigate ways in which processing speed and cognitive processes are related. Auditory processing speed and its relation to language development may be domain general and a function of overall processing speed, or alternatively, language development may be related to auditory processing speed in a domain specific way, independent from global processing speed. To disentangle these ideas, four specific relations were examined, namely, those between (a) ATI and language ability, (b) IT and IQ, (c) ATI and IT, and (d) ATI, IT, and age, in a sample of 4-6 year old children. Overall, results provided support for the relation between ATI and age, and IT and age, but failed to support relations between ATI and language, IT and intelligence, or ATI and IT, beyond that which is driven by age. In the context of this study, the results suggest that chronological age may be the primary factor impacting the relations between types of processing speed - when age is accounted for, limited relations between types of processing speed remain.

## Auditory Processing Speed and Language Ability

Surprisingly, ATI was not significantly correlated with overall measures of language ability, despite prior evidence to the contrary. However, some interesting trends are worthy of further discussion. In particular, there were significant correlations between ATI and receptive language measures. The *PPVT-4*, a measure of receptive vocabulary, and the Sentence Structure subtest of the *CELF-P2*, a measure of receptive language structure, were both significantly correlated with ATI threshold. While these results are not conclusive, these correlations lead to questions about whether auditory processing speed may be more strongly related to receptive language abilities and to theories about why that may be. This is not the first study to find a link with receptive language specifically. Previous research has also shown that performance on auditory perceptual variables requiring processing of rapid temporal information is correlated with performance on receptive language tasks in children with Developmental Language Disorder (Tallal, Stark, & Mellits, 1985) and the latency of auditory cortical responses in the right hemisphere was most accurate in identifying presence of impairments in receptive language in children (Oram Cardy, Flagg, Roberts & Roberts, 2008).

Auditory processing speed can be measured using a number of different tasks, can be defined in different ways using different terminology, and can require multiple cognitive components (Miller, 2011; Protopapas, 2014). These inconsistencies can make it challenging to determine which component is interacting with other measures, such as language ability or intelligence. It may be that only certain constructs of auditory processing speed are related to language ability or, as presented by Protopapas (2014), that in order to establish theories of the link between auditory processing and language, considerations must be made for intermediary causal links, namely speech processing and phonological processing.

It is also possible that a relation between ATI and language ability does not exist and that our results are valid. Previous work in which auditory processing speed was measured using multiple behavioural methods has suggested that difficulties in auditory processing speed, and therefore, ATI, are not necessarily present in children with developmental language disorders. While some children with impaired language display difficulties with auditory processing speed, others perform similarly to their peers with typical development (Bishop et al., 1999). Although studies have shown a relation between ATI and language, it is possible that the relation described in those studies is influenced by other variables, and that ATI and language ability are not, in fact, related. More research is needed to disentangle the different components of processing speed and the ways in which they may or may not relate to cognitive processes.

## Information Processing Speed and Nonverbal Intelligence

Unexpectedly, we did not find a significant correlation between IT and PIQ. The relations between IT and FSIQ, VIQ, and PIQ are well substantiated within the literature (e.g., Edmonds et al., 2008; Nettelbeck & Young, 1989, 1990; Sheppard & Vernon, 2008; Williams et al., 2009). In many cases, it is timed tests of intelligence that are most closely related to processing speed (Park et al., 2015). The *WPPSI-III* PIQ score is composed solely of tasks that are untimed, in that there is no added bonus for completing the tasks quickly. Furthermore, previous work in children has demonstrated higher correlations between IT and VIQ than between IT and PIQ because in children, IT and VIQ are both influenced by fluid intelligence (Brand & Deary, 1982; Nettelbeck & Young, 1989), whereas in adults, fluid intelligence influences PIQ (Sheppard & Vernon, 2008). In our study, to obtain a measure of intelligence that was more independent from language ability and given the known influence of language ability on VIQ, we used PIQ to examine intelligence. Despite the established relation between IT and PIQ, we failed to find support for this relation. Therefore, in future studies, it would be valuable to include VIQ, PIQ, and FSIQ as measures of multiple constructs of intelligence, to provide flexibility in understanding how these constructs might relate differently to measures of processing speed.

In addition to differences in correlations between IT and measures of intelligence (i.e., PIQ versus VIQ), differences have been observed in the relations between IT and IQ under variable conditions. Some prior research has suggested that a significant correlation between IT and IQ is limited to those samples in which participants have IQs below the average range. Deary et al. (1989) observed contradictory results wherein IT and IQ were significantly correlated in a sample that included participants with IQ in the average to above average range, but included the caveat that a large sample is likely required to accurately identify this correlation. It is quite possible that the sample in the current study fell into one, if not both, of these categories. Our sample was not large enough to detect correlations of $r < .30$, and the IQ of our participants was (for the most part) in the average to above average range (i.e., only two participants obtained PIQ scores of less than 85).

Based on the previous literature, our results are surprising in a number of ways. We anticipated finding correlations between ATI and language and between IT and PIQ. Both of these relations are supported in the literature, albeit, using different combinations of auditory processing and IT tasks and language and intelligence tests. While our results do not support a domain general relation, we also did not find evidence of domain specific relations between ATI and language nor between IT and PIQ. Although the expected relations were not observed in this study, it is possible that these relations exist and that we simply failed to capture them based on these issues.

## Study Design Considerations

A number of study design factors may also have played a role in our unexpected findings. Our ATI task used a 4I 2AFC design. It is possible that this may not have been the most appropriate type of task for testing young children. In a study investigating frequency discrimination, children under the age of 8 years performed better on 6I tasks, which offered children the ability to compare and identify an odd-one-out stimulus (Sutcliffe & Bishop, 2005). In the present study, we observed that not all children clearly understood the initial instructions and thus needed additional support and explanation during the training phase. It is possible that, as a result of this task comprehension issue, some children's ATI performance was impacted. ASHA recommends not assessing auditory processing in children under 7 years or with a mental age below 7 years due to challenges associated with their understanding of the task and therefore test interpretability (Magimairaj & Nagaraj, 2018), although there are exceptions to this recommendation depending on task demands and the ability of the child. Alternatively, if the task has been designed for use with younger children, it can also be appropriate for use with children under 7 years (ASHA, 2005). The tasks in the current study, while designed for children, may have been too challenging for the children in our sample to understand and complete successfully. Providing 6I instead of 4I, as demonstrated by Sutcliffe and Bishop (2005), may have made the task more manageable for these young participants. As a result, we are currently creating new tasks designed specifically to measure auditory processing speed in young children, which take into consideration these recommendations about measuring auditory processing speed.

Although the expected relations were not observed in this study, we cannot conclude that they do not exist. The lack of clarity due to decisions made about the design of the study and inconsistencies in how auditory processing speed constructs are defined and measured create challenges in the interpretation of our results. In addition, previously established relations (i.e., between IT and IQ) were not observed. With the development of new auditory processing speed tasks for young children, measuring multiple constructs of auditory temporal processing using different, child-friendly behavioural tasks, we hope to investigate these relations in a more detailed manner in the future.

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# 3 The Behavioral Measurement of Auditory Temporal Processing: A Mixed Methodological Scoping Review

## Introduction

Auditory temporal processing can be broadly defined as the processing of incoming acoustic stimuli over time (e.g., Musiek et al., 2005; Rawool, 2006). Acoustic stimuli are composed of many different features (i.e., duration, frequency, intensity, etc.), and the extraction and processing of each of these occur independently and require different amounts of time before the sensory information from all features is integrated into one auditory percept (Näätänen & Winkler, 1999). In fact, different time domains are involved in the processing of auditory stimuli; fine temporal resolution produces short auditory percepts (1–5 ms) and short-term (10–30 ms) and long-term integration (150–300 ms) processes combine these percepts into auditory signals (Sidiropoulos et al., 2015). Given the multiple features that must be processed to form a unitary auditory signal, it is important to ensure that measurement of auditory temporal processing accurately identifies and differentiates the features and processes involved. This becomes particularly relevant in light of the fact that auditory temporal processing is measured using many techniques. A shared understanding of auditory temporal processing is imperative to ensuring consistency and reliability in its measurement across studies from different fields of research.

Auditory temporal processing has been studied using a variety of both verbal and nonverbal paradigms using both behavioral and electrophysiological approaches in studies of communication (i.e., speech, language and hearing; e.g., Benasich & Tallal, 2002; Buus, Florentine, & Poulsen, 1999; Leonard, 1998; McArthur & Bishop, 2005; Musiek et al., 2005), child development (e.g., Magimairaj & Nagaraj, 2018; Yathiraj &

Vanaja, 2015), aging (e.g, Lister, Besing, & Koehnke, 2002), and music (e.g., Donai & Jennings, 2016). In addition to many studies of individuals across the age span who have no impairments, a variety of disorder populations have been studied using these varied paradigms and approaches, including individuals with dyslexia (e.g., Hamalainen et al., 2013; Zaidan & Baran, 2013), autism (e.g., Oram Cardy et al., 2005), cognitive impairment (e.g., Edwards et al., 2017), schizophrenia (e.g., Moschopoulos et al., 2019), and auditory processing disorder (e.g., Bamiou, Musiek, & Luxon, 2001). Despite this widespread attention to and interest in the study of auditory temporal processing, there is an overall lack of alignment and consistency in how to define and measure it (Sharma et al., 2006). As described by Miller (2011), "auditory processing has become a buzzword that has almost as many meanings as there are people who use it" (p. 309). Due to its widespread measurement and use, careful and intentional use of terminology and accuracy in descriptions of auditory temporal processing measures is critical. The inconsistency in measurement and meaning can lead to confusion about how different constructs of auditory temporal processing relate to other variables (e.g., cognitive processes such as language). It is possible that not all constructs are related to all variables, but unless constructs are clearly defined and measurable, it is difficult to study how different constructs of auditory temporal processing are related to each other and to other abilities. Without clarity about the constructs being measured, research describing relations between and using these constructs is difficult to synthesize and interpret reliably.

The present review investigated current behavioral approaches to the measurement of auditory temporal processing in the experimental literature. Even though the term auditory processing alone has many meanings (Miller, 2011), we focused on temporal constructs of auditory processing because of their proposed role in our own field of research, child language development and disorders. Theories of language impairment propose that children who struggle to develop spoken language may have difficulty or show inefficiency in processing rapidly presented auditory information (e.g., Bailey & Snowling, 2002; Hartley & Moore, 2002), and a variety of paradigms and terminology related to auditory temporal processing have been used to explore this proposal. In our review, we sought not only to describe the ways in which auditory temporal processing is measured in the extant literature, but also the terms and definitions currently in use, with the ultimate goal of developing a proposal for clear and shared terminology going forward.

## Objectives

This mixed methodological scoping review sought to address three specific aims: (a) to record the terms currently being used to describe constructs of auditory temporal processing, (b) to describe the ways in which these constructs are currently being measured, and (c) to organize the terms, tasks, and constructs being used to measure auditory temporal processing. We focused this review on the last five years to obtain an overview of current approaches to auditory temporal processing measurement.

# Method

This scoping review followed the PRISMA-ScR guidelines (Tricco et al., 2018). We elected to use a scoping review because this method is particularly useful for mapping a specific area of research that has not been comprehensively reviewed before (Arksey & O'Malley, 2005). Both quantitative frequency analyses and some features from qualitative metasynthesis were used to analyze data extracted following the literature search. Due to the nature of the data we extracted and aims of our review, emphasis was not placed on the quality of studies included. Instead, we focused on the various descriptions and decisions made about the measurement of auditory temporal processing and the tasks themselves.

## Literature Search

A literature search was performed for the years 2015-2019. Databases searched include Scopus, PsycInfo, and PubMed. Search criteria were: “auditory” AND (“temporal” OR “speed” OR “duration”) AND (“acuity” OR “integration” OR “process*” OR “resolution” OR “precision” OR “perception”) AND NOT (“animal”).

## Data Collection

After removing duplicates, 6693 articles were returned from the literature search conducted in April 2020. After reviewing titles and abstracts, the full text of 217 articles was searched. 103 articles were included in the final extraction and analysis process. From these 103 articles, 108 tasks were analyzed. Articles were included if they assessed some construct of auditory temporal processing using a behavioural task in humans. Articles were excluded if they: (a) measured auditory temporal processing using only electrophysiological or neurological measures, (b) measured auditory temporal processing in animals, or (c) used other auditory features, such as frequency or intensity. Due to the complexity of auditory temporal processing and the importance of considering its individual constructs in its measurement, this review included only those tasks that included a changing temporal component.

The information that was extracted from articles fitting the inclusion criteria included: (a) the article citation, (b) the task name, (c) a description of the task, (d) the independent task variables, (e) the outcome(s) being measured, (f) the reported construct of auditory temporal processing being measured, (g) how the reported construct was defined, and (h) the field of the journal in which the article was published. Insomuch as was possible, the extracted data were recorded for each task. Task titles were recorded directly based on what each paper reported. Task descriptions were paraphrased but included information about the task and the process used to assess auditory temporal processing. Technological specifications were not recorded, as this information extends beyond the scope of this article. The independent task variables and outcome measure(s) were often reported and inferred as necessary based on the task description and the method and results sections of each study. *Construct* was defined as the variable that the task is purported to be measuring. Constructs were extracted from the task description when possible. If studies did not report the construct being measured in the task description, other sections of the study were searched (i.e., introduction, objectives, general method section). Construct definitions were only recorded if the study clearly and specifically described the meaning of a construct. Finally, field of study was recorded using the subject of the journal in which the study was published.

## Data Analysis

The data were analyzed quantitatively based on frequency analyses (how often tasks, terms, and definitions were used) and qualitatively through comparative analyses (how terms were used and how terms, task names, and definitions overlapped). Qualitative analyses were guided by principles of qualitative metasynthesis (Erwin et al., 2011; Green & Thorogood, 2018; Sandelowski et al., 1997). Qualitative metasynthesis, defined as “the theories, grand narratives, generalizations, or interpretive translations produced from the integration or comparison of findings from qualitative studies” (Sandelowski et al., 1997, p. 366), aims to “integrate and interpret patterns and insights systematically across qualitative investigations while also maintaining the integrity of the individual studies” (Erwin et al., 2011, p. 189). While this scoping review did not seek to integrate the findings from qualitative studies, it did seek to integrate and interpret qualitative descriptions about the behavioural measurement of auditory temporal processing. As such, the principles of qualitative metasynthesis were considered throughout data analysis. However, we recognize that this review does not entirely align with the purpose of qualitative metasynthesis. Qualitative coding techniques similar to primary techniques can be used in qualitative metasynthesis (Green & Thorogood, 2018), but due to the methodological nature of the data, thematic coding was not deemed suitable for addressing the objectives of this study.

# Results

## Task Name and Description

Task names and descriptions were recorded based on what each study reported. There were occasionally small variations in how task names were reported, but to maintain accuracy these were recorded exactly as listed in the paper (e.g., Gap Detection and Gap Detection Test). To account for these minor differences in task names, tasks were organized into categories based on the aim of the task (e.g., to detect a gap between tones). Based on the task descriptions, the tasks were grouped into five categories used to measure auditory temporal processing: Gap Detection (*n* = 63), Temporal Order

Judgment (*n* = 19), Duration Discrimination (*n* = 16), Rise Time (*n* = 4), and Other (*n* = 6). Table 3.1 displays the breakdown of tasks by category and task name.

Interestingly, tasks with the same task title could have important methodological differences that were not reported consistently across studies. These included considerations such as type of auditory stimuli (e.g., pure tone, noise, etc.), frequency of stimuli, durations of stimuli and gaps, how threshold is calculated, step size between stimuli in adaptive procedures, whether and how many practice trials occur, and number of experimental trials, in addition to differences in hardware being used (e.g., laptop, desktop, sound card, headphones, etc.). For example, within the Gap Detection category, there were two tasks named *Gap Detection*. One task employed a randomized gap detection paradigm, which included 9 different gap durations presented 16 times each in random order (Babkoff & Fostick, 2017). Participants were required to determine which tone pair contained a gap. Performance at each gap duration was assessed and each participant's gap detection threshold was the gap duration at which they achieved 50% success. The other gap detection task asked participants to select which tone pair contained a silent gap (ranging from 0-20 ms in 2 ms increments) using an adaptive procedure, and calculated the gap detection threshold by averaging the last 8 reversals (Zhang et al., 2015). Tasks in the *Temporal Order Judgment* category generally required the ordering of either spectral or spatial information. This was sometimes described in the task name (*n* = 5, 26%), but always described in the task description. *Duration Discrimination* tasks, again, consisted of two main variations: discriminating the duration of tones or of silent intervals. Much like the Temporal Order Judgment category, this was occasionally described in the task name (*n* = 5, 33%), but often not.

**Table 3.1 Task Frequency by Category**

| Category | Task Names | Number of Times Used |
|---|---|---|
| Gap Detection: Detect a gap between tones | Gap Detection | 2 |
| | Adaptive Test(s) of Temporal Resolution | 5 |
| | Gaps in Noise | 21 |
| | Random Gap Detection Test | 12 |
| | Gap Detection Test | 7 |
| | Gap in Noise Detection | 1 |
| | Temporal Resolution | 1 |
| | Gap Discrimination | 1 |
| | Gap Detection Threshold | 6 |
| | Gap In Noise | 3 |
| | Monaural vs Binaural Gap Detection | 1 |
| | Detection Threshold of Gap in Noise | 1 |
| | Gaps in Noise Detection Task | 1 |
| | Temporal Gap Detection | 1 |
| Temporal Order Judgment: Determine the order of tones | Dichotic TOJ | 1 |
| | Temporal Order Judgment | 4 |
| | Time-Order Judgment | 1 |
| | Auditory Temporal Order Judgment | 4 |
| | Spectral Temporal Order Judgment | 2 |
| | Spatial Temporal Order Judgment | 3 |
| | Threshold Speech of Auditory Processing | 1 |
| | Interaural Time Difference | 1 |
| | Auditory Temporal Order Threshold | 1 |
| | Temporal Information Processing | 1 |
| Duration Discrimination: Identify differences in length between tones or silences | Time Bisection Task | 1 |
| | Empty Intervals | 1 |
| | Empty vs Filled Intervals | 1 |
| | Duration Discrimination Task | 2 |
| | Duration Discrimination | 8 |
| | Auditory Duration Discrimination Task | 1 |
| | Duration Discrimination Using Pure Tone | 1 |
| | Interval Discrimination | 1 |
| Rise Time Discrimination: Distinguish differences in the rate of intensity increase over time | Sound Rise Time Discrimination | 1 |
| | Onset Discrimination - Rise Time | 1 |
| | Rise Time Discrimination | 2 |

| | | |
|---|---|---|
| Other | Auditory Processing Speed Task | 1 |
| | No Name | 3 |
| | Rate Discrimination Task | 1 |
| | Pulse Train Duration Discrimination | 1 |

All tasks involved a changing temporal component recorded as the *independent variable*. Examples of independent variables include the duration of the interstimulus interval, the duration of a tone, the duration of some component of the stimuli (e.g., rise time), or the duration of gaps inserted into noise. As a result of the differences in independent variables, different and, in some cases, multiple outcome measures were used to assess performance across tasks. Some type of auditory temporal processing threshold was used as one of the outcome measures in 86 tasks (80%). Thresholds were calculated differently for tasks, mostly through adaptive staircase procedures (*n* = 44) and randomized stimulus presentation (*n* = 55). Adaptive staircase procedures employed various staircases (e.g., 2-down 1-up or 3-down 1-up) to achieve different threshold percentages (e.g., 70.7% and 79.4%; Karmali et al., 2016; Kollmeier et al., 1988; Levitt, 1971). Tasks that used randomization to obtain a threshold of performance used a set number of stimuli and assessed performance at each target stimulus. Based on a pre-determined accuracy criterion (i.e., 50-75%), the stimuli at which participants meet that level of accuracy was determined to be the threshold. Other outcome measures included measures of accuracy (*n* = 12, 11%) and other measures (*n* = 12, 11%) such as reaction time, Weber fractions, and point of subjective equality (e.g., the point at which two responses are equally likely). Eight studies did not report outcome measures, although in some cases, it was possible to make an educated inference about what outcome measure would be used based on the task(s) being used (e.g., in studies using the Random Gap Detection Test, the likely outcome measure would be a gap detection threshold).

Although there were distinct categories of auditory temporal processing tasks, many of the task characteristics, both within and across categories, varied greatly. With the exception of three commonly used Gap Detection tasks (Adaptive Test of Temporal Resolution; Lister et al., 2006; Gaps in Noise; Musiek et al., 2005; and the Random Gap Detection Test; Auditec, 2015), which are fairly prescribed in how they are delivered, many of the tasks varied in their methodological specifications. Because there are so many specifications to consider both within tasks and categories and across tasks and categories, very little could be gleaned about the task specifications based on the task title, independent variable, construct reported to be measured, and field of study.

## Constructs

Constructs were not reported for 10 of the 108 tasks analyzed and constructs were not defined for 65 tasks. For the sake of clarity, constructs were collapsed to include: *temporal processing, temporal resolution, temporal discrimination, temporal perception, temporal acuity,* and *other*. Some studies reported multiple constructs being measured by their tasks of auditory temporal processing. Figure 3-1 summarizes the number of tasks reported to measure each construct. Figure 3-2 depicts the constructs reportedly measured by each task category.

## Construct Definitions

Construct definitions were included in 43 of the auditory temporal processing task descriptions. Identical construct definitions were used in 9 instances where multiple tasks

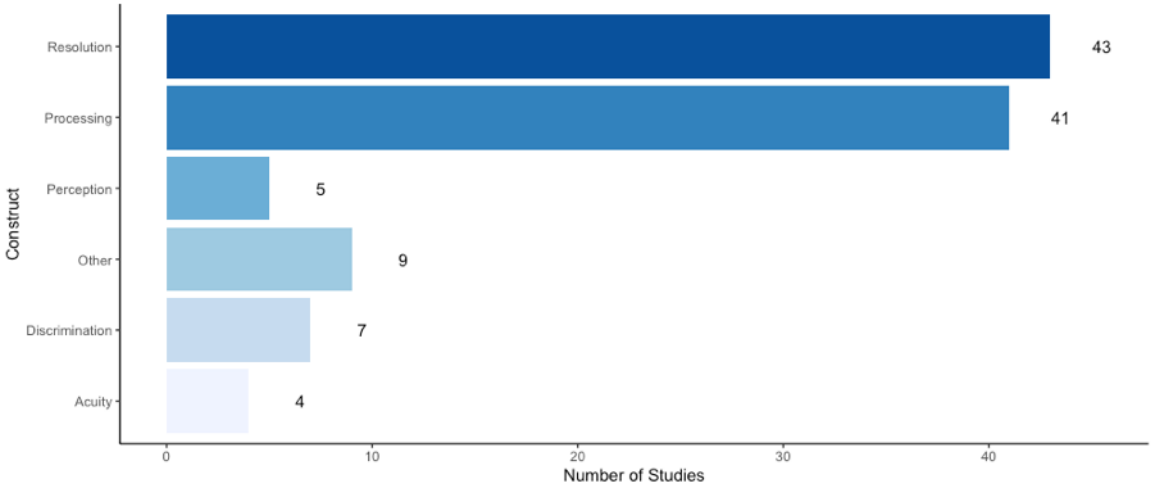

**Figure 3-1 Number of Studies by Construct.** Note. The *Other* construct included integration, order, skills, efficiency, and speed.

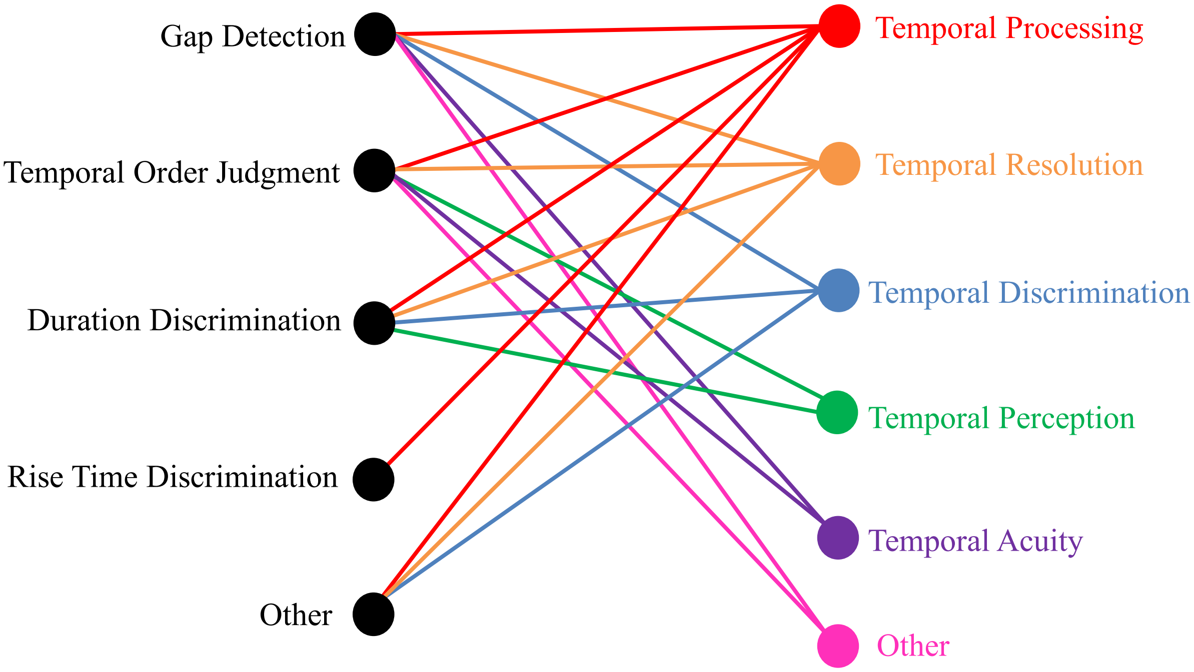

**Figure 3-2 Overview of Constructs Measured by Each Task Category**

were reported in one study, therefore, 38 unique construct definitions were provided. Overall, definitions across constructs made mention of some or all of three key factors: (a) used acoustic or auditory stimuli, (b) measured ability to detect change, and (c) detected change that was rapid and over time. At least one definition was provided for constructs of each category with the exception of the other Category (see number of occurrences for each construct in Table 3.2).

**Table 3.2 Number of Times Each Construct Category was Defined**

| Construct Category | Number of Definitions |
|---|---|
| Temporal Processing | 18 (17 unique) |
| Temporal Resolution | 24 (21 unique) |
| Temporal Discrimination | 5 (3 unique) |
| Temporal Perception | 2 |
| Temporal Acuity | 1 |
| Other | 0 |

Temporal processing tended to be defined more broadly than other constructs (e.g., “Patient’s ability to perceive temporal auditory characteristics,” Pedersen et al., 2017, p. 539), but in some cases, was defined more specifically (e.g., “Ability to perceive a sound or sound change within a period of time,” Fadel et al., 2018, p. 114). Temporal resolution was typically described more specifically, and was frequently defined as some variation of the ability to detect quickly occurring differences or changes in stimuli (e.g., “minimum time interval necessary for a subject to distinguish between distinct acoustic events,” Alvarez et al., 2015, p. 1702). This type of definition of Temporal Resolution aligns with Musiek and colleagues' (2005) variation of Plack and Viemeister’s (1993) definition, “the ability of the auditory system to respond to rapid changes in the envelope of a sound stimulus over time,” p. 608-609). Definitions of Temporal Discrimination focused on the ability to identify differences occurring quickly such as “allows us to detect small and sudden changes in sound stimuli" (Kumar et al., 2016, p. 310). Temporal perception and temporal acuity were both defined less frequently than the other three constructs. When descriptions were provided, Temporal perception was defined as the "perception of duration of sensory events" (Fornaciai et al., 2018, p. 1), while temporal acuity was defined as the "recognition of temporal cues in acoustic energy as the means to differentiate acoustic signals" (Alhaidary et al., 2019, p. 53).

## Constructs Measured by Different Categories of Tasks

Generally, each category of tasks is reportedly measuring many constructs, and many of the task names and constructs being measured are being used interchangeably in how researchers are reporting their measurement of auditory temporal processing. For example, temporal resolution is reportedly measured by Gap Detection tasks, Temporal Order Judgment tasks, Duration Discrimination tasks, and Other tasks (e.g., pulse train duration discrimination). Temporal processing is reportedly measured by Gap Detection, Temporal Order Judgment, Duration Discrimination, and Rise Time tasks.

Despite the substantial amount of overlap in how constructs are reportedly being measured, there are some patterns in how researchers are reporting which constructs different categories of tasks are thought to measure. The construct of temporal resolution is more often measured using Gap Detection tasks than with tasks in other categories. This aligns with studies stating that temporal resolution is most commonly assessed using the detection of short gaps in an ongoing sound (Günel et al., 2018). Surprisingly, despite certain tasks being designed to measure certain constructs (e.g., Gaps in Noise measuring temporal resolution; Musiek et al., 2005), not all studies using Gaps in Noise reported that the construct being was measured was temporal resolution. Other studies report using

Gap Detection tasks to measure temporal processing. Although all constructs were occasionally reported as being measured by Temporal Order Judgment tasks, they seemed to be most commonly used to measure the construct of temporal processing. Rise Time tasks were also exclusively described to measure temporal processing in some capacity. Duration Discrimination tasks were reported to measure a number of constructs, but each time temporal perception was described as being measured, it was by Duration Discrimination tasks with one exception. Overall, task categories were often described to be measuring multiple constructs and many of the construct definitions were quite similar.

## Discipline

Eleven disciplines were recorded by categorizing the topics of the journals in which studies were published. Table 3.3 provides a list of fields of study and examples of journals within that field. The studies were most often published in communication sciences and disorders, psychology, and otolaryngology journals. Gap Detection tasks appeared to be more often published in journals with a communication/audiology focus than other disciplines. Temporal Order Judgment tasks were generally published in journals with a psychology or communication sciences and disorders focus, while Duration Discrimination and Rise Time tasks were published mostly in journals with a psychology focus. The full data file can be accessed at this link: https://uwoca-my.sharepoint.com/:x:/g/personal/rsmyth5_uwo_ca/ES9fL6dymaVChjFLhdTc10EBLKiL8eJWkuXykvPzXEw1YQ?e=1tXZjl

**Table 3.3 Fields of Study and Examples of Journals in which Auditory Temporal Processing is Measured**

| Fields of Study | Examples of Journals |
|---|---|
| Communication Sciences and Disorders | Journal of Speech, Language, and Hearing Research; Journal of the American Academy of Audiology; CoDAS |
| Development and Developmental Disorders or Disabilities | Early Human Development; Journal of Autism and Developmental Disorders |
| Oto(rhino)laryngology | Brazilian Journal of Otorhinolaryngology; Journal of the Association for Research in Otolaryngology |
| Psychology | Neuropsychology; PsyCh Journal |
| Medical | Saudi Medical Journal; Journal of Stroke and Cerebrovascular Diseases |
| Rehabilitation | Journal of Rehabilitation Research & Development |
| Learning Disabilities | Journal of Learning Disabilities |
| Neurological Disorders | Epilepsy & Behavior |
| Aging | Frontiers in Aging Neuroscience |
| Brain | Brain Research; Brain and Language |
| Other | Attention, Perception & Psychophysics; Journal of Visualized Experiments |

## Discussion

This scoping review sought to organize and integrate information about behavioural approaches to the measurement of auditory temporal processing reported in the literature over the past five years. Specifically, we aimed (a) to record the terms currently being used to describe constructs of auditory temporal processing, (b) to differentiate the ways in which constructs are currently being measured, and (c) to organize the terms, tasks, and constructs that are used in the measurement of auditory temporal processing.

The behavioural measurement of auditory temporal processing is currently being labelled and described using a variety of inconsistent and overlapping terms and definitions, with different terms and definitions being used interchangeably. For example, auditory temporal processing and temporal resolution were often defined very similarly: "individual's ability to perceive brief sounds presented rapidly" (Babkoff & Fostick, 2017, p. 270) and "ability of the listener to perceive rapid changes in an acoustic signal" (Mussoi & Brown, 2019, p. 1328). This can create confusion regarding auditory temporal processing and its measurement (Miller, 2011). This confusion is amplified due to the range of disciplines across which auditory temporal processing is measured (e.g., communication sciences and disorders, psychology, aging, development and developmental disorders, etc.). Task descriptions also report differences in the way that tasks are designed and run. Comparing performance on auditory temporal processing tasks across studies is difficult when tasks with the same name are said to be measuring different constructs but employ the same or similar design. In addition to these sources of confusion, the constructs that are reportedly being measured may be defined in very similar or very different ways, leading to the question of what is really being measured by different tasks of auditory temporal processing.

The aims of this review focused on the collation and organization of how auditory temporal processing is currently being measured behaviourally in the experimental literature. Despite the aforementioned inconsistencies, variability, and overlap, our review did reveal preliminary patterns that can help organize the way in which we discuss behavioural measurement of auditory temporal processing going forward. Gap Detection tasks are most often used to measure temporal processing and temporal resolution. This may raise the possibility that task differences (e.g., random gap detection versus adaptive paradigm) could highlight differences between the constructs being measured by the task. In other words, Gap Detection tasks may measure different constructs depending on the task specifications. Based on the constructs identified in this review, Duration Discrimination tasks may be uniquely measuring temporal perception. Temporal Order Judgment tasks and Rise Time tasks were mostly common described as measuring temporal processing. Musiek et al. (2005) describe four subcategories of auditory temporal processing: (a) temporal masking, (b) temporal ordering or sequencing, (c) temporal integration or summation, and (d) temporal resolution or discrimination. In this review, many studies described temporal processing as the construct being measured, but perhaps temporal processing is better considered a superordinate category that can be broken down into more specific auditory temporal processes, some of which may have been described in this review, such as temporal resolution, temporal perception, or temporal discrimination.

This scoping review addressed only the temporal component of auditory processing. There are many other components, both non-speech and speech, to consider that interact with the temporal features in processing acoustic information (e.g., frequency, intensity, modulation, and speech perception; Rawool, 2006). An expanded scoping review that encompasses all measures of auditory processing would be a valuable, albeit complex, endeavor requiring thoughtful organization and interpretation.

The review presents an opportunity for researchers with a shared interest in auditory temporal processing to attend to the discrepancies and inconsistencies in how tasks are labelled and designed, in how constructs are measured and defined, and in how we discuss these considerations in our work. The confusion that can arise from the overlap highlighted in this study must be addressed, through shared methodologies, constructs, and definitions (Miller, 2011). The summary of the ways in which auditory temporal processing tasks and constructs are being used and studied across disciplines provided by the present review can inform this next step of addressing the overlap and inconsistencies. One place to begin clarifying the way in which we discuss the measurement of auditory temporal processing is by establishing specific and measurable auditory temporal processing constructs through a cross-discipline Delphi study (Hasson et al., 2000), which could serve to establish specific definitions and measures of constructs of auditory temporal processing, thereby providing shared terminology in the experimental literature in the future.

Disentangling the overlap and inconsistency in the measurement of auditory temporal processing through the use of tasks proposed to measure different constructs in the same individuals is an additional step that could be taken moving forward. The categories of auditory temporal processing measurement highlighted in this scoping review may be helpful in guiding the establishment of these constructs. There is ample support for the use and measurement (through random gap detection) of temporal resolution as one construct of auditory temporal processing. A second potential construct may be that of temporal perception, reported to be measured through discrimination tasks in which, not only must participants detect some feature of a stimulus, but they must also discriminate between that and another stimulus to respond (e.g., duration discrimination or discrimination of gap durations). As Musiek et al. (2005) describe, temporal ordering may be a more specific construct than temporal processing that is measured through Temporal Order Judgment tasks. Considerations for the other components of auditory processing should also be made in the development and implementation of a shared set of auditory temporal processing constructs. With these clarifications about its measurement, auditory temporal processing research across disciplines will become more clear and accessible to others studying auditory temporal processing.

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# 4 Development of Tasks to Measure Auditory Temporal Processing in Children: A Pilot Study with Adults (Pre-Registration)

## Introduction

*Auditory temporal processing* is the way in which the temporal information of an acoustic stimulus is perceived over time (Musiek et al., 2005). Auditory percepts (the sounds we perceive) are created through the integration of rapidly presented auditory information by chunking incoming acoustic information into units across time (Cowan, 1984; Näätänen & Winkler, 1999). The resolution of the signal improves when this is done more quickly, which may have implications for the development of language (Paula Tallal, 2000). The measurement of auditory temporal processing is complex and has been conducted both behaviourally and neurophysiologically using a variety of passive and active paradigms. Auditory temporal processing has been measured in infants, children, and adults (e.g., Benasich & Tallal, 2002; Lister et al., 2002; Shinn et al., 2009). Most studies investigating auditory temporal processing in children have been limited to those over 7 years of age. For example, the gaps-in-noise test (Musiek et al., 2005), a task in which participants hear silent gaps of varying sizes within periods of white noise and must signal when they have heard the gap, has been used to assess temporal resolution in children aged 7-18 years (Shinn et al., 2009), to assess temporal resolution in children aged 8-10 years born prematurely (Durante et al., 2018), and to differentiate between children aged 8-9 years with and without dyslexia (Zaidan & Baran, 2013). Duration discrimination tasks, in which participants must observe differences in the duration of tones, and rise-time discrimination tasks, in which participants differentiate between the time from stimulus onset to maximum amplitude of different tones, have been used to measure auditory temporal processing as it relates to language development in children aged 8-12 years with developmental language disorder (Richards & Goswami, 2015), which is characterized by persistent impairments in language development that are not associated with a differentiating condition (Bishop et al., 2017). Despite its widespread measurement using a variety of behavioural tasks in children, many auditory temporal processing tasks require active participation and are not well-designed for young children. As a result, use of such tasks for clinical assessment of children under 7 years is not recommended by the American Audiology Associate (AAA; 2010) and American Speech-Language-Hearing Association (ASHA; 2005) due to the potential for difficulties with interpretation of test results.

Given the challenges in using traditional behavioural measures, efforts have been made to measure auditory temporal processing in children under 7 years using tasks created specifically for younger populations. For example, in the Auditory Processing Speed task, children must differentiate between tone pairs of different frequencies separated by various inter-stimulus intervals (ISIs) (e.g., Avanzino et al., 2015). To make this task suitable for younger children, Avanzino and colleages included age-appropriate rewards, included a training session to teach the associations, and made the task interactive using a touch screen. Children were trained to associate two tone pairs (one pair with two tones of the same frequency and one with two different tones) with two monkeys popping out of barrels. Upon hearing a tone pair, the child touched the barrel of the associated monkey to make the monkey pop out of its barrel. As outlined in Smyth et al. (2020, Chapter 2), more research is needed of auditory temporal processing and its various constructs in younger children (e.g., 2-6 years) due to the limited number of studies to date, variability in results across those studies, and, in some cases, the young participants having difficulty understanding the tasks typically used. To accurately measure auditory temporal processing behaviourally in young children, new child-appropriate tasks must be designed to address the potential for difficulties with test interpretation while also considering the constructs that the tests are designed to measure. Intentional consideration of the constructs measured by auditory temporal processing tasks is one way to ensure that findings can be interpreted accurately (Smyth & Oram Cardy, 2020, Chapter 3).

One area of interest in the literature on auditory temporal processing in children is its relation with cognitive abilities (such as language and intelligence) and other aspects of processing (such as information processing speed). Relations between auditory temporal processing and language have been posited because of the way in which poor resolution of the auditory percepts may influence the early development of language (Tallal, 2000). Kail (1994) suggested the hypothesis of generalized slowing, which purports that individuals with developmental language disorder perform more slowly on tasks of processing speed, including auditory processing and information processing. *Information processing speed* is the time required to perceive and interpret incoming sensory information and make some observation about it, and is often measured across sensory modalities as an overall index of thinking, reasoning, and remembering (Coyle et al., 2011; Julesz & Hirsh, 1978; Kail, 2000). While there is an established relation between information processing speed and intelligence (e.g., Brand & Deary, 1982; Sheppard & Vernon, 2008), there is mixed support for a relation between auditory temporal processing and language ability, with some studies finding relations (e.g., Benasich & Tallal, 2002; Oram Cardy et al., 2005) and others failing to find support for this relation (e.g., Bishop et al., 1999).

Research examining whether information processing speed and auditory temporal processing operate as part of one domain general system or as separate domain specific processes depends on the ability to measure these constructs in various populations of various ages. These relations have been studied mostly in children over 7 years in and to some extent in infants, but, as described above, are less well studied in children between 2-6 years. This is a period that sees tremendous growth in the language system (arguably more so than the school-aged period), and the extant experimental literature supports significant developmental changes in auditory temporal processing (e.g., Fox et al., 2010) and information processing speed (Kail, 2000) during this period as well. Therefore, it is critical to develop valid and reliable measures of auditory temporal processing (and information processing speed) if we are to better understand the relations between these processes and early language development. Without such tasks, it is unclear whether or how relations between these abilities exist during this critical period of language development.

Efforts to develop measures of information processing speed suitable for young children have seen some success. *Inspection Time* (IT) is one measure of information processing speed and is the time required by a participant to observe a sensory input with some distinct feature and distinguish that feature (Vickers & Smith, 1986). In the same way that auditory temporal processing has been difficult to measure in children under 7 years, IT has been traditionally measured using a task that was difficult for young children to understand and complete. In response to this problem, Williams et al. (2009)

developed the *Benny Bee IT task*, which was designed specifically for young children (i.e., 4 years old). The Benny Bee IT task has been validated against the standard IT task in a group of adults (Williams et al., 2009).

Behavioural tasks of auditory temporal processing offer the advantage of being widely available, less expensive than electrophysiologic tasks, and easier to administer to participants (Jerger & Musiek, 2000). While many behavioural auditory temporal processing tasks have been used in the experimental literature (Smyth & Oram Cardy, 2020, Chapter 3), the large number of task variables that can be changed mean tasks measuring constructs of auditory temporal processing can be inconsistent. Based on the results of Smyth and Oram Cardy (Chapter 3), we determined that it was important and feasible to create tasks to measure two constructs of auditory temporal processing, temporal resolution and temporal perception, in children. Temporal resolution, the auditory system's response to rapid sound stimulus changes (Musiek et al., 2005), has been measured through various gap detection tasks. Temporal perception, the perception of the duration of sensory events (Fornaciai et al., 2018), is thought to be measured using duration discrimination tasks.

To improve the behavioural measurement of auditory temporal processing in young children, we developed three child friendly tasks that are intended to measure different constructs of auditory temporal processing. Two tasks were developed based on the results of Smyth and Oram Cardy (2020, Chapter 3): the Gap Detection task, which measures temporal resolution, and the Duration Discrimination task, which measures temporal perception. We also developed a third auditory task to parallel the (visual) Benny Bee IT task. It employs a backward masking paradigm, which is similar to those used in visual IT tasks. Auditory IT tasks (e.g., Brand & Deary, 1982; Irwin, 1984) have also employed masking (backward and forward) between tones. These auditory IT tasks involve pitch discrimination between two tones separated by a masking noise that is either a white noise (e.g., Brand & Deary, 1982; Irwin, 1984) or tones (e.g., Nettelbeck et al., 1986). Given our broader research interest in understanding the relation between information processing speed and auditory temporal processing, a more comparable auditory cognate of the Benny Bee IT task would help us consider whether the similarities in demands of the two (auditory and visual) IT tasks might support interpretation of relations between information processing speed as measured using IT tasks and other measures of auditory temporal processing. Because of the differences between this task and other auditory IT tasks, we will refer to this task as the Auditory Backward Masking task.

## Objectives

The purposes of this study are to investigate, in the same sample, (a) the relation between auditory temporal processing (specifically, temporal resolution, temporal perception, and auditory backward masking) and language ability, (b) the relation between information processing speed and intelligence, and (c) the relation between auditory temporal processing and information processing speed. To our knowledge, these constructs have not been measured and compared within a single sample before, which has limited the ability to consider domain general and domain specific relations between them. In this study, we expect to find some shared variance in auditory temporal processing tasks and to see negative relations between auditory temporal processing tasks and language ability (i.e., as auditory temporal processing threshold gets smaller, language ability is stronger), negative relations between information processing speed and intelligence (i.e., as information processing speed thresholds get smaller, intelligence is higher) and positive relations between auditory temporal processing and information processing speed (i.e., decreased auditory temporal processing thresholds will coincide with decreased information processing speed thresholds).

An additional purpose of this study is to pilot three child friendly measures of auditory temporal processing in a sample of healthy adults to determine the feasibility of their future use for young children. The impetus for the development of these tasks was the observation that children aged 4-6 years had difficulty understanding the task requirements of a previously used auditory temporal processing task (Smyth et al., 2020, Chapter 2). The eventual goal in developing these new behavioural auditory temporal processing tasks is to use them alongside tests of information processing speed, language ability, and intelligence to assess the relations between processing speed and cognitive abilities, such as intelligence and language, in young children.

# Proposed Method

## Subjects

Seventy participants will be recruited for this study. To detect a medium correlation of ~.30, a sample of 70 provides power of about 82% (Cohen, 1988). The expected correlations between processing measures (auditory temporal processing and information processing speed) and cognitive variables (language ability and intelligence) range from .30-.40. Adults between the ages of 18 and 45 with no developmental or neurological conditions will be recruited. Participants will have normal hearing and normal or corrected to normal vision by self-report. Participants will be recruited through the OurBrainsCAN database housed at Western University, through social media, and through posters displayed around Western University's campus.

## Testing Procedure

Each participant will complete a series of tasks of language ability, intelligence, auditory temporal processing, and IT at Western University. Participants will complete one session of about 90-120 minutes. Computer tasks (the Benny Bee IT task and auditory temporal processing tasks) will be run on a Lenovo T440 computer with an Intel® Core$^{TM}$ i7-4600U CPU @ 2.10 GHz 2.70 GHz running the 64-bit Windows 7 Professional operating system. An Elo Touchsystems CRT monitor, model ETI 725C-4UWE-3 (100-240 V, 1.5 A, 60/50 Hz, P/N 454000-000) will be attached to the computer to ensure timing for the Benny Bee IT task is accurate and precise. Timing of this specific monitor for the Benny Bee IT task has been tested and validated (Smyth et al., 2017). The auditory temporal processing tasks will use the same computer. Additionally, Panasonic RP-HC200 headphones and a Roland Corporation Model UA-25EXCW external sound card will be used to present the auditory stimuli.

### Language Ability

Three measures of language ability will be used. The *Communication Checklist – Self Report* (*CC-SR;* Bishop, Whitehouse, & Sharp, 2009) is a 70-item questionnaire that participants will fill out about themselves with statements about communicative weaknesses and communicative strengths. The items from the *CC-SR* create three composites: Language Structure, Pragmatic Skills, and Social Engagement. In this study, the Language Structure composite will be used. The *Test for the Reception of Grammar – 2nd Edition* (*TROG-2*; Bishop, 2003) assesses the understanding of grammatical contrasts using 20 constructs. In the *TROG-2*, each construct is tested four times with different stimuli. *TROG-2* standard scores will be calculated. The final measure of language ability will be the Oral Language Subscale of the *Weschler Individual Achievement Test – 2nd Edition* (*WIAT-II*; Wechsler, 2005). The Oral Language Subscale provides a standard score and is made up of tasks of listening comprehension and oral expression assessing skills such as receptive vocabulary, literal and inferential comprehension, word fluency, auditory short-term recall, story generation, giving directions, and explaining sequential steps (Wechsler, 2005).

Each of the language ability measures was chosen based on its ability to measure different aspects of language ability in adults aged 18-44 years. The *WIAT-II* provides information about expressive vocabulary, expressive language structure, and receptive vocabulary and the *TROG-2* estimates receptive language structure. Finally, the *CC-SR* offers insight into participants' use of language.

### Intelligence

Intelligence will be measured using the *Wechsler Abbreviated Scales of Intelligence-2nd Edition* (*WASI-II*; Wechsler, 2011). All four subtests will be administered to provide a measure of Full Scale IQ (FSIQ), Verbal Comprehension Index (VCI; analogous to Verbal IQ or VIQ), and Perceptual Reasoning Index (PRI; analogous to Performance IQ or PIQ). The VCI is composed of the Vocabulary and Similarities subtests whereas Block Design and Matrix Reasoning make up the PRI. The four subtests are used to calculate the FSIQ.

### Inspection Time

The Benny Bee IT Task (https://www.neurobs.com/ex_files/expt_view?id=197) has been validated to measure IT in 4-year-old children and shown to relate to intelligence, including FSIQ, VIQ, and PIQ (Williams et al., 2009). The Benny Bee IT Task uses backward masking to measure IT. Two identical flowers appear and participants are told that Benny is the fastest bee in the world and will appear on one of the flowers. Both flowers are quickly covered by identical images of seven bumblebees, which appear for the purposes of masking the original stimulus. Participants are then asked to identify which flower Benny landed on before the other bees (the mask) appeared. The time between Benny appearing on the flowers and the mask appearing changes depending on the accuracy of previous trials. The Benny Bee IT task uses an adaptive staircase algorithm to produce an IT threshold, which is the shortest time in ms at which the participant identifies the flower that Benny landed on with 79% accuracy (Williams et al., 2009).

## Auditory Temporal Processing

A series of three measures of auditory temporal processing will be used in this study. The three measures use duration discrimination, gap duration discrimination, and backward masking to assess auditory temporal processing. The three tasks were programmed using PsychoPy and will be run in PsychoPy (Peirce & MacAskill, 2018). Auditory stimuli for these tasks were created and digitized at a sampling rate of 44.1 kHz using Praat software version 6.1 (Boersma & Weenik, 2019).

All three tasks employ the same set of instructions and visual stimuli but use different auditory stimuli to assess auditory temporal processing. In each task, participants see three robots appear one at a time. Each robot appears in line with an auditory cue. The participant is asked to select the robot that sounds different than the other two robots, employing a 3 AFC paradigm. This type of paradigm is recommended for use with younger children in assessing frequency discrimination, another measure of auditory processing (McArthur & Bishop, 2004). Each of these tasks uses a 3 down, 1 up adaptive staircase to determine the threshold in ms at which participants are 79% accurate (Levitt, 1971; Peirce & MacAskill, 2018; Wetherill & Levitt, 1965). This produces the same threshold as the IT threshold produced in the Benny Bee IT task. Each of the auditory temporal processing tasks consists of 50 trials or 8 reversals, whichever occurs first. One step is 2 ms and trials will be adjusted by step sizes of 8, 4, 4, and 1. Each task will begin with 10 practice trials to ensure participants recognize the auditory feature they are being asked to discriminate.

### Duration Discrimination Task

The duration discrimination task involves discriminating between tone durations to identify the tone with the shorter duration (code file linked here: https://uwoca-my.sharepoint.com/:u:/g/personal/rsmyth5_uwo_ca/Ec1hq4tkiEhDhgVT1DnYFOMB3UKTlJ1P-hxWNM-oTY35xg?e=N442kk). Three 440 Hz tones will be presented to participants. Two tones will contain the standard interval, which will be 250 ms, while the third duration will range from 2 ms to 250 ms (target interval) using an adaptive staircase procedure. The first target interval is 125 ms in duration. The duration discrimination threshold will identify the smallest tone duration necessary to discriminate it from the two standard 250 ms tone durations. The interstimulus interval is 750 ms. Figure 4-1 depicts the duration discrimination task.

### Gap Detection Task

The gap detection task asks participants to select the interval that contains a longer gap between two 250 ms tones (code file linked here: https://uwoca-my.sharepoint.com/:u:/g/personal/rsmyth5_uwo_ca/Ef5y8PCu4oZKmXq6RGKFpIQBgo28gVmJYzzdGxAH9f-ERw?e=yHS19l). The two standard intervals contain

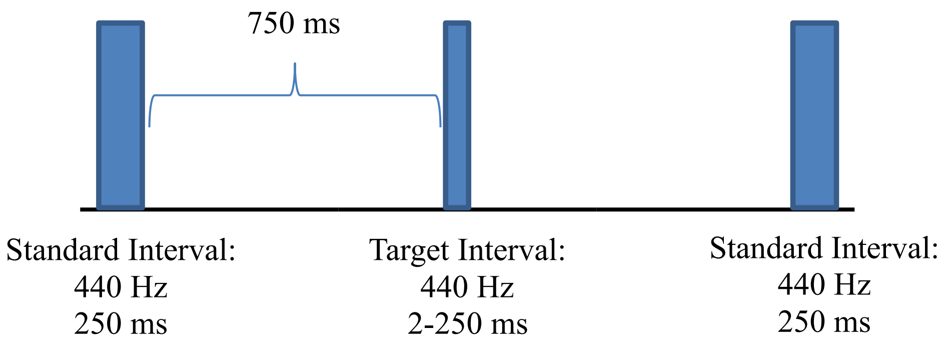

**Figure 4-1 Duration Discrimination Task**

a gap of 0 ms whereas the target interval contains a gap ranging from 2-250 ms. The first target interval contains a gap of 125 ms. The gap detection threshold will identify the smallest gap duration required to successfully discriminate the target interval from the two standard intervals containing the 0 ms gap. The interstimulus interval is 750 ms. Figure 4-2 depicts the gap detection task.

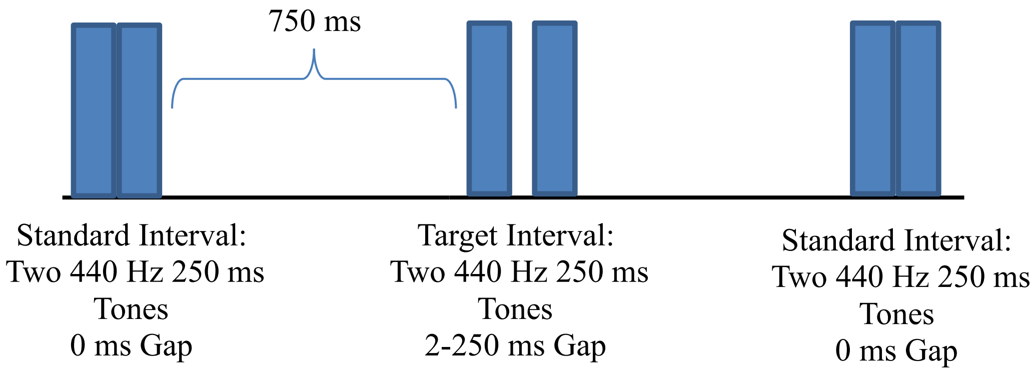

**Figure 4-2 Gap Detection Task**

## Backward Masking Task

The backward masking task was designed to be an auditory cognate to the Benny Bee IT Task. In this task, the standard intervals consist of 1 second of white noise and the target interval contains a brief tone, ranging from 2-250 ms, followed by 1 second of white noise (code file linked here: https://uwoca-my.sharepoint.com/:u:/g/personal/rsmyth5_uwo_ca/EbFDLEPIUOlGkIAqTk0T64QBKwCgOctYSS1A6Pcw6pJNug?e=MStMh7). The first target interval contains a tone of 125 ms. In this task, due to longer intervals and in an effort to keep the time spent completing the task reasonable, the interstimulus interval is 500 ms. The backward masking threshold will determine the smallest tone duration prior to the masking noise necessary to discriminate it from the two standard intervals consisting of only the masking noise. The backward masking task is depicted in Figure 4-3.

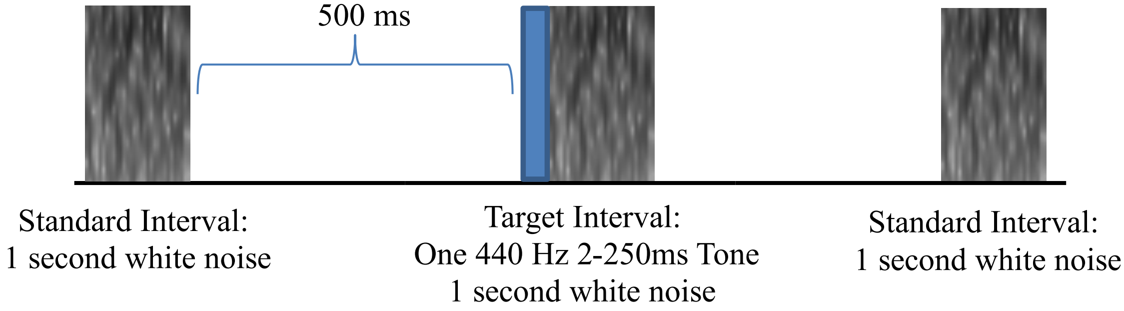

**Figure 4-3 Backward Masking Task**

## Data Analysis Plan

To meet the aims of this study, we will use Pearson product moment correlations to measure the relations between the following variables: (a) *CC-SR* Language Structure Scale Score, (b) *TROG-2* Standard Score, (c) *WIAT-II* Oral Language Composite Standard Score, (d) *WASI-II* VCI, (e) *WASI-II* PRI, (f) *WASI-II* FSIQ, (g) Gap Detection Threshold, (h) Duration Discrimination Threshold, (i) Backward Masking Threshold, and (j) Benny Bee IT Threshold. The following correlations will be run based on the aims of this study: (a) between measures of language (*CC-SR, TROG-2, WIAT-II*) and measures of auditory temporal processing (Gap Detection Threshold, Duration Discrimination

Threshold, Backward Masking Threshold), (b) between measures of intelligence (*WASI-II* VCI, PRI, FSIQ) and the Benny Bee IT Threshold, and (c) between measures of auditory temporal processing (Gap Detection Threshold, Duration Discrimination Threshold, Backward Masking Threshold) and the Benny Bee IT Threshold.

## Anticipated Results

The primary aims of this study are to determine the ways in which auditory temporal processing and information processing speed relate to other cognitive abilities, namely language ability and intelligence. In addition, we seek to determine whether the auditory temporal processing tasks would be feasible and appropriate to use with children, some of whom may have a language disorder or other neurodevelopmental disorders such as autism or ADHD. We anticipate finding negative correlations between auditory temporal processing tasks and language ability. We also anticipate finding negative correlations between information processing speed and measures of intelligence. Finally, we expect performance on auditory temporal processing and information processing speed tasks to positively correlate. More specifically, we anticipate performance on the duration discrimination task, the gap detection task and the backward masking task will correlate because these tasks all measure temporal aspects of auditory processing. Additionally, we expect to see tasks of auditory temporal processing positively correlate with performance on the Benny Bee IT task.

Alternatively, it is possible that we will see relations between performance on auditory temporal processing tasks and language ability, and between performance on the Benny Bee IT task and intelligence, but that there will not be a relation between auditory temporal tasks and performance on the Benny Bee IT task. In this case, the processing abilities may be operating in domain specific systems and unrelated due to their dependence on different sensory systems (i.e., auditory vs visual). If this is the case, it is unlikely that auditory temporal processing tasks will relate to measures of intelligence and that the Benny Bee IT task will relate to language ability. Interestingly, in this case, the VCI relies to an extent on verbal ability and may relate to auditory temporal processing performance, despite the absence of a relation between auditory temporal processing measures and the Benny Bee IT task and between auditory temporal processing measures and other types of intelligence.

Finally, we expect the auditory temporal processing tasks to produce thresholds of duration discrimination, gap detection and backward masking. We anticipate that participants will understand and be able to follow the task instructions. If the three tasks of auditory temporal processing function as expected, they may offer feasible options to measure auditory temporal processing in children younger than 7 years.

## Implications

This aim of this study is to investigate the relations between constructs of auditory temporal processing and how they relate to information processing speed and other cognitive abilities, such as language and intelligence. Should performance on auditory temporal processing tasks relate to information processing speed, language ability and intelligence, inferences about the way in which processing (auditory temporal processing and information processing speed) functions across sensory systems and how it relates to other cognitive abilities may be made. Other considerations may need to be made to pilot these tasks successfully with children. If performance on all three of these tasks is too related in this sample of adults, it may suggest that all three tasks are measuring very similar constructs and each task may not be necessary to obtain a measure of auditory temporal processing. In this case, it may be worth eliminating a task from the protocol when children are tested.

A secondary aim is to determine the feasibility of using three newly developed tasks to measure auditory temporal processing in young children. We predict that the constructs they are intended to measure (temporal resolution, temporal perception, and backward masking) will relate to information processing speed, language, and intelligence. We also predict that these three tasks will be feasible options to measure constructs of auditory temporal processing in children younger than 7 years. If this goal is met, these tasks may help in the measurement of auditory temporal processing in a population that has been traditionally difficult to assess using behavioural tasks because of challenges such as test interpretation difficulty (AAA, 2010; ASHA, 2005). Following such a result, we would be able to be pilot their use in the assessment of auditory temporal processing in children younger than 7 years.

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# 5 An Assessment of the Feasibility of Online Testing for Auditory Temporal Processing

## Introduction

With the arrival of the COVID-19 pandemic, many researchers have been required to suspend in-person data collection. This has motivated the search for new ways of collecting data, including the possibility of moving to Internet-based research as a way to avoid physical proximity between researchers and participants. For example, a repository of developmental psychology tasks has been created for researchers to share tasks designed for remote assessment in an open-access format (Oliver, 2020). While some researchers are developing new tasks for online use, others have attempted to move formerly in-person experimental paradigms online.

For researchers who, like us, were in the midst of gathering in-person data using behavioural measures of auditory temporal processing when the pandemic arrived, the question becomes one of whether online testing is feasible for paradigms of this nature. *Auditory temporal processing* involves the perception and integration of acoustic information over time. Its behavioural measurement often involves tasks in which participants must make some decision or observation about a difference between auditory stimuli relating to duration, frequency, or intensity. One way to gather information about an individual's auditory temporal processing ability is through the use of tasks that produce a threshold. For example, in gap detection tasks, a gap detection threshold is calculated based on the shortest duration at which a participant can reliably detect a silent gap (e.g., Fitzgibbons & Wightman, 1982; Musiek et al., 2005; Trehub, Schneider, & Henderson, 1995). Auditory temporal processing thresholds, measured using a variety of constructs, have been shown to relate to other variables such as age (e.g., Fox et al., 2010), language (e.g., Benasich & Tallal, 2002; Oram Cardy et al., 2005), and reading ability (e.g., Richardson et al., 2004) in children. Behaviourally, tasks often involve thresholds at the millisecond level and thus require accurate and precise timing mechanisms. Therefore, it becomes critical to determine whether it is possible to measure auditory temporal processing thresholds, which rely on accurate and precise timing and measurement of auditory signals, online.

Even before the pandemic, the last two decades have seen behavioural researchers investigating what factors make Internet-based research possible and feasible. In 2004, the Board of Scientific Affairs' Advisory Group on the Conduct of Research on the Internet released a report summarizing the advantages of and the issues associated with engaging in online research (Kraut et al., 2004). Advantages include the ease of recruiting large samples, many of which are more representative of the general population than smaller lab-based samples, and the fact that it may require less time spent on recruitment, scheduling, and data collection (Berinsky et al., 2012; Grootswagers, 2020a; Kraut et al., 2004). Many participants can participate at the same time, without the need for extra examiners (Woods et al., 2015). Challenges associated with Internet-based research have shifted as solutions for previous issues have been developed, with many aspects of research having been adjusted to better fit an Internet-based context. For example, research ethics and privacy have been a widely discussed issue (e.g., James & Busher, 2015; Nosek et al., 2002). In the time since Internet-based research started, advances and solutions to informed consent and data privacy have been found so that Internet-based research can occur ethically and safely.

In determining whether to run a study in person or as an Internet-based study, research groups face many considerations. Extra attention must be paid to the research decision-making process because of the nature of Internet-based research. In Internet-based research, participation occurs asynchronously, and the lack of face-to-face interaction can be a change for researchers transitioning to these new methods of research. Rodd (2019) described detailed considerations related to the lack of face-to-face participation in Internet-based research such as identifying concerns associated with data quality, identifying the worst case scenario, adding within-experiment safeguards, and designing and pre-registering experiment-specific exclusion criteria. Certain studies may require more or less preparation in transitioning to Internet-based research and in some cases, the move to an Internet-based study may not be appropriate.

The impetus for the literature review described here was our need to determine whether it would be feasible to use an Internet-based study to collect data with three auditory temporal processing tasks we had created for children under seven years of age. Within the context of this study, many considerations needed to be made in determining whether it would be appropriate to collect auditory temporal processing data through an Internet-based format. The three auditory processing tasks include a gap detection task, a duration discrimination task in which participants must identify the shorter of two tone durations, and a backward masking task in which participants must identify the segment in which a short tone plays before a mask of broadband noise. All three tasks employ an adaptive staircase 3-alternative forced choice paradigm. To ensure children are engaged and understand the tasks, each signal plays with the appearance of a robot so that participants can be asked “Which robot sounded different?” The three auditory temporal processing tasks were created in PsychoPy using a combination of the Builder interface and Code Components (Peirce & MacAskill, 2018).

The aim of this paper was to review evidence and considerations from the extant literature that can be used to inform feasibility of moving auditory temporal processing tasks online for use in an Internet-based study.

# Method

## Literature Search

Scopus and PsycINFO were searched using a combination of the following terms: “auditory”, “temporal”, “processing”, “online”, “remote”, “virtual”, “test*”, and “assess*”. In addition to searching databases, due to the current push towards online learning and Internet-based research and to capture grey literature, such as dissertations and pre-prints, we searched Google Scholar using similar search terms. Finally, we searched Twitter using the #BeOnline2020 hashtag because of its connection with the Behavioural Science Online conference in June 2020, which focused on performing research online.

## Analysis

To determine the feasibility of accurately and precisely assessing auditory temporal processing using an Internet-based study, we sought research regarding the accuracy and precision of timing and the quality of stimuli in Internet-based research, particularly as it related to auditory stimuli. However, research using other modalities (namely vision) were also included where relevant.

# Results

## Hardware, Software, and Timing

Within the lab setting, the testing protocol is controlled and all testing is performed using the same combination of hardware and software. When research becomes Internet-based, each participants' hardware and software is different (Anwyl-Irvine et al., 2020). In addition to the differences in hardware and software, internet browsers change with participants. Each of these differences along with variables such as the use of keyboards (Neath, 2011) can impact timing mechanisms.

Two recent studies have thoroughly reviewed the timing accuracy and precision of different experimental stimuli using various operating systems, software programs, and internet browsers. Anwyl-Irvine and colleagues (2020) used four Internet-based software programs: (a) Gorilla, (b) jsPsych, (c) Lab.js, and (d) PsychoJS across three internet browsers: (a) Chrome, (b) Edge, and (c) Firefox, using two operating systems: (a) Windows and (b) macOS. With these combinations of software, internet browsers, and hardware, the authors assessed the delay and variance of the delay of stimuli for visual display duration and reaction time accuracy. Their tests of timing mechanisms showed that the smallest visual display delay was observed using Chrome on a Windows computer. Visual display duration tests using Lab.js showed the smallest amount of variance. Otherwise, the platforms perform similarly. To test measures of reaction time, two laptops (one Windows and one macOS) were also used based on the differences in keyboards relative to those used with desktops. Laptops produced slightly more variance than desktop computers in this timing test, and software platforms did not perform equally across operating systems and internet browsers (see Anwyl-Irvine et al., 2020 for specific patterns).

In addition to reviewing timing mechanisms in Internet-based studies, Bridges et al. (2020) also compared the timing accuracy and precision of Internet-based experiments to the timing accuracy and precision of lab-based studies of the same experimental stimuli. In the lab-based study, the authors assessed the timing properties of five different types of stimuli: (a) reaction times, (b) visual durations, (c) visual onset, (d) audio onset, and (e) audiovisual sync. They used three operating systems (Win10, macOS, and Ubuntu) with each of six software packages (PsychToolBox, Presentation, PsychoPy, E-Prime, Open Sesame, and Expyriment). For the Internet-based study, they included the additional variable of internet browser (Chrome, Firefox, Edge (Standard), and Safari). Software packages also differed between lab-based and Internet-based studies due to differences in functionality. The Internet-based software packages were: (a) PsychoPy, (b) Gorilla, (c) jsPsych, (d) Testable and (e) Lab.js. The Internet-based stimuli included: (a) reaction times, (b) visual durations, and (c) audiovisual sync because certain timing mechanisms could not be measured online. Overall, Bridges et al. (2020) observed that precision in lab-based studies and Internet-based studies were both reasonable, but the *lags*, or the constant error (associated with accuracy), for the Internet-based studies, were longer than the lab-based studies.

In another study, which used Flash and Javascript to run Internet-based experiments, duration of auditory stimuli was quite precise (maximum variability of 11 ms), but the actual duration was longer than expected (Reimers & Stewart, 2016). Discrepancies in the duration of 1000 ms tones was about 20 ms, but could be as discrepant by as much as 33ms longer when used in Internet-based research. Of particular concern were the auditory and visual stimulus onset asynchronies, which demonstrated a lagging auditory stimulus, which ranged from 35-104 ms behind the visual stimulus (Reimers & Stewart, 2016). See Table 5.1 for a summary of the described studies.

Many of the studies described above involved fairly simplistic stimuli such as a single tone or a single visual component and performance did not rely on short or dynamic presentation times. Crump et al. (2013) explored the fidelity of the Amazon Mechanical Turk system, an Internet-based experiment platform, with a series of RT experiments, rapid stimulus presentation experiments, and learning studies. The RT experiments were successfully replicated online and performance followed patterns observed in-person. The three rapid stimulus presentation experiments required millisecond control in the visual modality. Experiments that involved longer stimulus presentation (80 ms or longer) were replicated, but those involving shorter stimulus presentation (64 ms or shorter) were not, which may indicate difficulty conducting experiments with very short stimulus presentation times, albeit, using visual stimuli (Crump et al., 2013). Studies investigating the timing precision and accuracy of complex auditory stimulus presentations are needed before conclusions about the transferability of these results to the timing of auditory stimuli can be made.

The studies described above used computers (desktop and laptop) as the hardware components in timing tests (Anwyl-Irvine et al., 2020; Bridges et al., 2020; Reimers & Stewart, 2016), but other types of hardware that could be used in Internet-based research include tablets and mobile devices. Anwyl-Irvine and colleagues (2020) surveyed over 200,000 participants about their operating system and browser information. They determined that while 77% of survey respondents were using desktop or laptop computers, 20% were using mobile devices and 2% were using tablets.

### Table 5.1 Summary of Timing Tests Performed in Large-Scale Timing Studies

| Study | Hardware | Software Platforms | Browser | Measurements Tested |
|---|---|---|---|---|
| Anwyl-Irvine et al., 2020 | Windows Desktop Running Windows 10 Pro | Gorilla Experiment Builder | Chrome 76 | Visual Duration Accuracy |
| | 2017 Apple iMac | jsPsych | Chrome 75 | RT Accuracy |
| | | Lab.js | Firefox 68 | |
| | | psychoJS | Firefox 69 | |
| | | | Safari 12 | |
| | | | Edge 44 | |
| Bridges et al., 2020 | Windows: PC<br>Linux: PC<br>2019 Mac Mini | Lab-Based | | |
| | | PsychoPy<br>Psychophysics Toolbox<br>OpenSesame<br>Expyriment<br>NBS Presentation<br>E-Prime | NA | RT<br>Visual durations<br>Visual onset<br>Audio onset<br>Audiovisual sync |
| | | Internet-Based | | |
| | | PsychoPy/ PsychoJS | FireFox | RT |
| | | -Gorilla | Chrome | Visual durations |
| | | jsPsych | Safari | Audiovisual sync |
| | | lab.js | Edge | |
| | | Testable | Edge Chromium | |
| Reimers & Stewart, 2016 | Desktop (Dell OptiPlex 9010 running Windows) | Flash | Microsoft (Internet Explorer or Edge) | Auditory Duration |
| | Laptop (Lenovo Flex 2 running Win 10) | JavaScript | Firefox | Visual Duration |
| | | | Chrome | SOA between Auditory and Visual Onset<br>Test-Retest |

It is important to consider the ways in which participants may be participating in Internet-based research and either establish exclusion criteria based on participants' devices (e.g., exclude participants using mobile devices; Theodore, 2020) or ensure that the timing on devices being used is considered accurate and precise.

Recommendations to avoid having timing error impact results include performing many trials or testing many participants. These recommendations may protect against large variability within the sample. In the absence of many trials or many participants, high precision is required (Bridges et al., 2020). Variability in response time in particular seems to be observed due to the differences in hardware associated with Internet-based research. In light of the potential for variability between participants, within-subject designs are superior. For example, using measures such as relative RT as opposed to absolute RT can reduce concerns about between-subject variability (Anwyl-Irvine et al., 2020; Bridges et al., 2020; Pronk et al., 2020).

## Auditory Stimulus Presentation

While much of the research comparing online to in-person performance to date has focused on the presentation of visual stimuli (as summarized by Reimers & Stewart, 2016), within the context of measuring auditory temporal processing, it is important to consider and evaluate the suitability of online experiments for auditory stimulus presentation. The quality of the audio signal presented is considered in a number of ways in lab-based experiments and can easily impact the results of an auditory experiment. These considerations should also be made when running Internet-based tasks.

Following a study demonstrating that online participants perform similarly to in-lab participants in sound continuity judgment tasks (McWalter & McDermott, 2019), a recent series of studies using in-person and online data collection examined pitch representation and harmonic and inharmonic sound discrimination used an adaptive staircase procedure that altered f0. McPherson and McDermott (2020) reported that online participants performed as well as lab participants as long as testing for earphone/headphone use was maximized and instructions were followed. Headphones, which partly cover the ear to reduce noise from external sources, improve the signal-to-noise ratio for the stimuli presented in the experiment by reducing the distance between the eardrum and the signal (Woods et al., 2017). In doing so, headphones provide greater control over the auditory stimuli presented. Headphones also provide a way to present auditory stimuli to both ears simultaneously or separately to one or both ears, which is another method to control the presentation of auditory stimuli (Woods et al., 2017). To ensure participants followed instructions, training was provided and participants were removed using hypothesis-neutral screening procedures. This was done by testing a group of participants in the lab to obtain a threshold for the best two-thirds of in-lab participants. Online participants who did not meet that threshold were excluded (of note, using these stringent screening procedures, 63.5% of online participants were excluded from analysis).

The ASA PP Task Force on Remote Testing (2020) describes the challenges associated with earphones, loudspeakers, and sound cards when testing remotely such as losing signal, inability to reduce environmental noise, and controlling the auditory stimulus. To combat these challenges, the Task Force suggests solutions such as shipping the required technology (e.g., a whole computer with earphones, or an external sound card and earphones), or testing stimulus playback across a number of operating systems and internet browsers to ensure stimulus playback will not be interrupted. Employing a protocol such as a validated headphone screening (Milne et al., 2020; Woods et al., 2017) can exclude participants who are not wearing headphones from completing the tasks, which can help control the sound presentation of Internet-based auditory research.

# Discussion

Overall, the literature review suggested that Internet-based testing is generally possible, but hardware, software, timing, and stimulus presentation need to be carefully considered. While no research or report to date has specifically addressed the feasibility of conducting behavioural measurement of auditory temporal processing online, information gleaned from the research along with resources about Internet-based research are helpful in determining whether it might be possible to reliably collect auditory temporal processing data behaviourally through an Internet-based study.

## Hardware, Software, and Timing Considerations

The combination of hardware, software, and browser used in Internet-based studies can impact timing accuracy and precision (e.g., Anwyl-Irvine et al., 2020; Bridges et al., 2020; Reimers & Stewart, 2016). Before committing to collecting data online using behavioural auditory temporal processing tasks, testing using different combinations of operating systems and internet browsers for the purposes of assessing the accuracy and precision of timing needs to be performed because it is not recommended to apply the results of the currently described timing studies to other Internet-based testing scenarios (Bridges et al., 2020). Additionally, Crump et al. (2013) highlighted the possible constraints of Internet-based research on paradigms relying on very short stimulus presentation times. While their research focuses on visual stimuli, it is worth noting that their timing thresholds, like behavioural auditory temporal processing tasks, rely on millisecond level differences between stimuli. Should short stimulus presentation times present timing challenges in auditory stimuli as well, it may not be feasible to measure auditory temporal processing behaviourally using Internet-based research.

One benefit of many behavioural tasks of auditory temporal processing is that performance does not rely on response time. An observation must be made about the stimuli (e.g., the duration of a tone or the duration of a silent gap), but the length of time required to respond is not important. This can account for motor differences and eliminate RT as a confounding variable in measuring auditory temporal processing, particularly in young children. Because RT does not necessarily impact the results in behavioural measures of auditory temporal processing, the between-subject variability in response time noted in previous research because of hardware and keyboards (e.g., Anwyl-Irvine et al., 2020; Bridges et al., 2020; Neath et al., 2011) may not be a significant concern.

## Auditory Stimulus Presentation Considerations

Another currently unknown entity is how well the quality of the presentation of auditory signals can be maintained in the context of Internet-based testing. Because behavioural auditory temporal processing tasks rely on millisecond level differences between stimuli, too much external noise or any distortion of signal could impact individual thresholds enough to affect results. Although McPherson and McDermott (2020) and McWalter and McDermott (2019) were able to show comparable results between online data collection and in-person data collection using more complex auditory stimuli, they did not use ms level temporal adjustments. Based on performance screening measures in one study, approximately 65% of online participants were excluded (McPherson & McDermott, 2020). While there are many possible reasons for this that may be unrelated to the auditory stimulus presentation (e.g., inattention or fatigue), it will be important to consider these, and other, reasons in the context of the online measurement of auditory temporal processing. If it is possible to rule out the quality of auditory stimulus presentation as impacting performance in online tasks of auditory temporal processing, Internet-based research may be feasible in its measurement. However, it will first be necessary conduct research directed at evaluating this issue, such as by comparing performance in online auditory temporal processing tasks to that of the lab-based setting.

## Conclusions

Testing auditory temporal processing online shows promise. Other auditory tasks using adaptive staircase procedures have been used in Internet-based studies and performance has been shown to compare to lab-based studies (McPherson & McDermott, 2020; McWalter & McDermott, 2019). However, it remains important to test the accuracy, precision, and quality of stimuli in the context of behavioural auditory temporal processing tasks due to the impact differences in hardware, software and browsers can have, particularly on timing at the millisecond level. Moving forward, timing tests should be performed with behavioural auditory temporal processing tasks using various combinations of hardware, software, and Internet browsers to ensure that timing accuracy and precision are appropriate and that the quality of the auditory stimulus presentation is not impacted so as to not impact participant performance.

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# 6 General Discussion

Previous research has supported a relation between auditory temporal processing and language ability (e.g., Benasich et al., 2006; Oram Cardy et al., 2005; Tallal, 2000; Tallal & Piercy, 1973), and between information processing speed and cognitive abilities such as intelligence (e.g., Coyle et al., 2011; Grudnik & Kranzler, 2001) and language (e.g., Kail, 1994; Miller et al., 2001). In this dissertation, I sought to investigate the nuanced ways in which auditory temporal processing and information processing speed relate, in addition to the ways in which they each relate, respectively, to other cognitive abilities, namely language ability and intelligence. While these relations have been studied previously, they have not been studied together in the same participant sample. This dissertation aimed to determine the ways in which these variables related, and whether the relations best reflect a domain-general processing system or domain-specific processes, functioning separately. To achieve this aim, I planned to measure auditory temporal processing behaviourally along with inspection time (a measure of information processing speed), language ability, and intelligence, in a series of experimental studies. Although the ultimate direction of this dissertation took a step back to disentangle questions outside of the original overall aim, the collective results of the studies outlined in the previous chapters return to a place where the original questions may be investigated with better clarity and understanding than possible before. This chapter provides an overview of relevant findings and key implications of the studies described in Chapters 2, 3, 4, and 5, and discusses future directions emerging from this dissertation.

# Relevant Findings and Implications

## Chapter 2

Chapter 2 investigated the relations between auditory temporal processing, information processing speed, language ability, and nonverbal intelligence in children aged 4-6 years. Surprisingly, the expected correlations were not significant between auditory temporal processing and overall language ability using the *Clinical Evaluation of Language Fundamentals (CELF-P2;* Wiig et al., 2004) Core Language Score, or between information processing speed, as measured by the Benny Bee IT task (Williams et al., 2009), and nonverbal intelligence as measured by the *Wechsler Preschool and Primary Scale of Intelligence* (*WPPSI-III;* Wechsler, 2002). Auditory temporal processing and information processing speed were significantly related to each other and were both, as expected, related to age. Regressions run on auditory temporal processing threshold and IT threshold were significant, but the only individual significant predictor was that of age on IT threshold. Post-hoc hierarchical regression analyses revealed that, once age was removed from the regressions, the variance accounted for beyond that of age was not significant in either model.

The unexpected results of this study led to questions about the relations between auditory temporal processing and language, and, perhaps more surprisingly, to questions about the relations between IT and nonverbal intelligence. To shed light onto these questions, clarity about the constructs measured in tasks of auditory temporal processing was required. In addition, further investigation of information processing speed, as measured by IT, and how it relates to intelligence, both verbal and nonverbal, in 4-6 year old children was needed. These new questions and implications led to the development of the studies planned in Chapters 3 and 4.

# Chapter 3

In response to the unexpected results in Chapter 2 and due to inconsistencies in how auditory processing is defined and measured (Miller, 2011; Sharma et al., 2006), Chapter 3 sought to define and organize the various constructs of auditory temporal processing and identify the behavioural tasks used to measure it through a qualitative methodological scoping review. The scoping review identified 108 tasks from 103 articles. Analysis of task name and descriptions in these articles identified five main categories of behavioural auditory temporal processing tasks: Gap Detection Tasks, Temporal Order Judgment Tasks, Duration Discrimination Tasks, Rise Time Discrimination Tasks, and Other Tasks. Within each of these categories, tasks employed a variety of methodological variations in stimulus presentation (e.g., randomized versus adaptive), adaptive staircases chosen (e.g., 2-down 1-up versus 3-down 1-up), and accuracy criterion (i.e., 50-75% range). Tasks were reported to measure six constructs: temporal processing, temporal resolution, temporal discrimination, temporal perception, temporal acuity, and other, all of which, when defined, included description of some or all of three key factors: (a) used acoustic or auditory stimuli, (b) measured ability to detect change, and (c) detected change that was rapid over time.

Each category of tasks was reported to measure many of the constructs, which appeared to be used in an interchangeable manner in reporting how auditory temporal processing was measured in the different studies. Despite this overlap, some patterns did emerge in how constructs were reportedly being measured. Temporal resolution was often measured using Gap Detection tasks. Temporal Order Judgment tasks and Rise Time Discrimination tasks were both reported to measure temporal processing more than other constructs. Duration Discrimination tasks, while reportedly measuring multiple constructs, was, with one exception, the only category of task that was described as measuring temporal perception. Task categories were all described to be measuring multiple constructs, many of which were defined in similar ways. While many studies reportedly use behavioural tasks of auditory temporal processing to measure temporal processing, perhaps temporal processing might be better considered a superordinate category, within which other constructs such as temporal resolution, temporal perception, and temporal discrimination exist and should be identified.

This scoping review examined one component, namely the temporal component, of auditory processing. An expanded review that includes other components of auditory processing such as frequency, intensity, modulation, and speech perception (Rawool, 2006) would also contribute to better clarity and organization of auditory processing measures and definitions. With this summary of information available, a cross-discipline Delphi study (Hasson et al., 2000) could serve to establish specific definitions and measures of constructs of auditory temporal processing, thereby provided a shared language in the experimental literature in the future.

## Chapter 4

In an extension of the results of Chapter 3, three child friendly tasks of auditory temporal processing were designed and programmed using PsychoPy (Peirce & MacAskill, 2018). A gap detection task was designed to measure temporal resolution, a duration discrimination task was designed to measure temporal perception, and a backward masking task was designed to act as an auditory cognate of the Benny Bee IT task (Williams et al., 2009). Chapter 4 provides a pre-registration plan for returning to the original aim of this dissertation: to investigate relations between auditory temporal processing and language ability and between information processing speed and intelligence, and how these types of processing relate to one another. Due to COVID-19, planned in-person data collection for this chapter could not be completed. Instead, Chapter 4 lays out the justification for this study, describes the methodology in detail, and describes the expected results and anticipated implications of this study.

The study planned in Chapter 4 sought to investigate, in the same sample, (a) the relation between auditory temporal processing (specifically, temporal resolution, temporal perception, and auditory backward masking) and language ability, (b) the relation between information processing speed, as measured by inspection time, and intelligence, and (c) the relation between auditory temporal processing and information processing speed. In this study, we expected to find some shared variance in the three tasks of auditory temporal processing, and anticipated negative correlations between auditory temporal processing thresholds and language ability. We also expected negative correlations between information processing speed and intelligence, and positive correlations between auditory temporal processing and information processing speed.

In addition to the three aims described above, Chapter 4 also was intended to serve as a pilot trial of three child friendly measures of auditory temporal processing. A sample of healthy adults was planned to assess the feasibility of these tasks prior for use with young children. One concern with the auditory temporal processing task used in Chapter 2 was that children aged 4-6 years had difficulty understanding the instructions. With the development of these behavioural tasks that all used the same 3IFC paradigm, the goal is to eventually use them to assess the aims listed above in a sample of young children.

# Chapter 5

With the arrival of COVID-19 and the transition to remote working, I sought to determine whether Internet-based research may provide an opportunity for the study planned for Chapter 4. This would include collecting data with the newly developed tasks of auditory temporal processing in an online setting. Due to the nature of the tasks, there were many considerations to be made about whether their use in an Internet-based format would be appropriate. To determine whether this might be feasible, I reviewed the available evidence and considerations from the extant literature that could be used to determine whether behavioural tasks measuring auditory temporal processing could be used in an Internet-based study.

A literature search geared towards assessing auditory temporal processing accurately and precisely in Internet-based research identified two main categories of considerations in transitioning to this format: (a) hardware, software, and timing, and (b) auditory stimulus presentation. Different combinations of hardware (e.g., type of device, make and model of device, built in or external components, etc.), software (e.g., program used to design and deliver the experiment), and browser create many opportunities for timing inaccuracies and inconsistencies, and can also impact the quality of the auditory signal in Internet-based research. Studies show that the timing accuracy and precision of reaction time, audio duration, visual duration, audio onset, visual onset, and audiovisual sync can all be impacted, even with the use of simple stimuli, and with various hardware, software, and browser combinations (Anwyl-Irvine et al., 2020; Bridges et al., 2020; Reimers & Stewart, 2016). Studies using more complex stimuli such as rapidly presented stimuli encountered difficulties, suggesting that studies using these types of stimuli may not be feasible online (Crump et al., 2013). When using complex auditory stimuli, screening for earphone/headphone use can reduce external noise and improve signal resolution (Woods et al., 2017).

Although testing auditory temporal processing online appears promising, preparatory validation of hardware, software, and timing, and the presentation of auditory stimuli needs to be pursued prior to proceeding with Internet-based research. Timing tests should be performed with the specific stimuli and experimental design because there are too many variables to simply infer whether testing under different conditions might be accurate and precise.

## Overall Implications

The overall aim of this dissertation, to investigate the relations between auditory temporal processing, information processing speed, and other cognitive factors, namely, language ability and intelligence, combines the work of two lines of research that have each been well studied but require integrated consideration. Although the results of the studies reported here lead to a place where, moving forward, the overall aim of this line of research remains the same, additional considerations about the nature of these relations and their implications can be made.

Learning about the ways in which these lines of research interrelate may help inform the way in which we understand the relation between auditory temporal processing and language development and therefore improve our understanding about the development of language as it occurs in typical development and neurodevelopmental disorders. The knowledge gained from this dissertation suggests that the two possible explanations of processing and language development remain possibilities. Auditory temporal processing and language may be related in a domain-specific manner, or auditory temporal processing may be related to language as one component of overall processing. That said, if the relation is domain-specific in nature, and isolated to the auditory system, we would not expect to see the relations between auditory temporal processing and information processing speed we observed in the study reported in Chapter 2. Protopapas (2014) described one method that can be used to assess the domain-specific versus domain-general hypothesis through the use of control tasks. If auditory temporal processing has a domain specific relation with language, performance on control tasks should be preserved if the tasks do not involve auditory temporal processes. The use of control tasks enables the identification of differences in performance that may indicate difficulty specific to auditory temporal processing.

In the context of this dissertation, the question about whether IT is a control task arises. IT does not measure auditory temporal processes, but if, as proposed by Tallal and colleagues (1993), children with DLD exhibit pansensory (i.e., across multiple sensory modalities) temporal processing difficulties, IT may not provide a control measure. Tasks of both auditory temporal processing and information processing speed rely on the ability to process temporal information, but in different sensory modalities, which may indicate that IT tasks are not control tasks when measuring auditory temporal processes. The correlation between auditory temporal processing and information processing speed seen in this dissertation may, then, suggest that these relations are domain-general in nature and support the processing speed accounts of DLD (e.g., Kail, 1994; Miller, 2014).

If the Benny Bee IT task described in this dissertation is not a suitable control task, moving forward, it may be worth employing a better control task in the investigation into these relations to determine their nature. If, as described above, difficulties with auditory temporal processing reflect difficulties in temporal processing in other sensory modalities, any temporal processing task would not be an appropriate control. Is there a task that does not rely on temporal processing, but does measure one’s information processing speed? The answer to this question may rely on the way in which different temporal processing constructs relate. Temporal processing may be understood in a number of ways. The first is the processing of quickly occurring information. In this case, response time is less important than the ability to process the quickly occurring incoming information accurately. The second is the quick processing of information, where the information itself is not necessarily brief, but the time required to process the information is. Finally, it may be understood as processing information that is quickly changing and measured by one’s ability to identify a change that occurred quickly. With these notions in mind, it becomes difficult to envision a processing speed task that does not rely on temporal processing in some way.

In thinking more deeply about the relations of interest in this dissertation, age requires specific consideration. In Chapter 2, its relation to the other variables demonstrated the need to consider the possible impact of age on the way in which results are interpreted. As previously described, auditory temporal processing and information processing speed have both been shown to improve with age (e.g., Fox et al., 2010; Kail, 1991). These developmental changes in auditory temporal processing and information processing speed were supported in the results of Chapter 2; older children were more accurate at identifying shorter thresholds on both the Bird Task and the Benny Bee IT task than younger children. The influence of age on performance in tasks of auditory temporal processing and information processing speed may account for some of the shared variance across types of processing. That is to say that the relation observed between auditory temporal processing and information processing speed could be impacted by the developmental nature of these two types of processing. If this relation is driven primarily by their shared developmental change, different inferences should be made than if their relation stems from a reliance on the recruitment and use of similar processes. In the first instance, auditory temporal processing and language ability may be operating in a domain-specific way despite the shared variance between auditory temporal processing and information processing speed associated with age. In this type of scenario, it also becomes important to ensure that age and measures of language are not correlated before concluding that the relation between auditory temporal processing and language is domain-specific. Alternatively, if age is one of multiple factors influencing shared variance, the domain-general hypothesis may persist. With this knowledge, it becomes important to consider the ways in which age may play a role in how these relations are interpreted in the design of future studies.

An additional factor to consider in interpreting the relations between types of processing and cognitive factors is the way in which these variables interact with auditory IT. The results of the scoping review in Chapter 3 made it clear that the measurement of auditory temporal processing is variable and can share many features with tasks that measure auditory IT. Many of the independent variables measured in tasks of auditory temporal processing include those used to assess auditory IT, for example, frequency, duration, intensity, and spatial location (e.g., Brennan et al., 2015; Deary, 1995; McCrory & Cooper, 2005; Olsson et al., 1998; Parker et al., 1999; Vercillo & Gori, 2015; Zajac & Nettelbeck, 2018). The similarity between these tasks leads to questions about how similar the constructs being measured by these tasks might be. If IT tasks are thought to measure information processing speed, we might expect information processing speed, at least as measured by auditory IT, to be related to constructs of auditory temporal processing. Auditory IT and visual IT are also related (e.g., Brand & Deary, 1982; Deary et al., 1989; Nettelbeck et al., 1986). As such, we would expect auditory temporal processing and information processing speed to be related. These relations and comparisons may provide additional support for the domain-general hypothesis, or the processing speed account of DLD (Kail, 1994; Miller, 2014). Overall, based on the results of the studies in this dissertation and the supporting literature, it is clear that the two streams of research, auditory temporal processing and language development and information processing speed and intelligence, must be combined and studied as one in an effort to better understand the ways in which processing ability might relate to language development, particularly in the context of understanding neurodevelopmental disorders such as DLD.

## Future Directions

Many considerations about the measurement of auditory temporal processing arose through the studies of this dissertation. Measuring complex processes in young children not only requires that the task is sensitive and able to measure the processes in question, but that the task is both understood by and capable of engaging children. Despite efforts to design and use simple and engaging tasks, the measurement of auditory temporal processing is complex and involves multiple cognitive processes (Protopapas, 2014), such as working memory and attention (Magimairaj & Nagaraj, 2018), and other listener variables such as motivation and fatigue (Jerger & Musiek, 2000). All of these variables and processes need to be considered when assessing children's auditory temporal processing ability. In future studies of auditory temporal processing in children, including measures of other cognitive factors beyond language ability and intelligence, such as attention and working memory would be beneficial, particularly to determine the ways in which performance on these tasks may relate to some other process not currently being measured.

An additional consideration regarding the measurement of auditory temporal processing using behavioural tasks in adults and in children is the variety in the tasks being used and the ways in which constructs are being defined. As mentioned in Chapter 3, a cross-discipline Delphi study may support researchers interested in auditory processing to develop a shared terminology for the measurement of auditory processing. Comparing the performance of one sample across different tasks of auditory processing may help explain and organize the differences in constructs being measured by various tasks, and the differences in how variance is shared across tasks may inform the ways in which auditory processing is related to other processes.

Over the last several decades, and particularly in response to COVID-19, Internet-based research is becoming more prominent. While Internet-based studies afford researchers large, representative samples, and faster recruitment, scheduling, and data collection (Berinsky et al., 2012; Grootswagers, 2020b; Kraut et al., 2004), there are many study design decisions that depend on the manner of data collection and need to be geared towards Internet-based data collection from the initial stages of planning. Internet-based research traditionally uses large-scale, asynchronous data collection, which, as summarized in Chapter 5, requires thoughtful planning, although synchronous data collection is also possible (Rodd, 2019). In contemplating the use of Internet-based data collection for the measurement of auditory temporal processing, the evaluation of timing accuracy and precision was important to consider, but additional considerations are of equal importance, and in certain instances, may be determining factors in the decision to transition a study into an online format.

Reflecting on the original overall aim of this dissertation, Internet-based research may not be the most appropriate method to meet this aim, particularly in samples of young children. Many of the considerations associated with measuring auditory temporal processing in children in-person described above, such as issues with understanding instructions, paying attention, motivation, or fatigue (Jerger & Musiek, 2000; Magimairaj & Nagaraj, 2018; Norbury et al., 2020; Protopapas, 2014), would also apply to scenarios in which children are assessed online. Additional challenges associated with testing online can include the inability to transition all tasks online (e.g., *WPPSI-III* or *WASI-II* Block Design, Wechsler, 2002, 2011) and the cost associated with using standardized tests online (Norbury et al., 2020). Participation may be possible synchronously through a video-call, which is used successfully in qualitative research (Archibald et al., 2019), although the potential need for support at home remains. Internet-based studies have been run with infants (Zaadnoordijk, 2020) and older children (aged 12-13 years, Norbury et al., 2020), but their use with children aged 4-6 years may present unique challenges.

## Conclusions

This dissertation sought to investigate the relations between auditory temporal processing, information processing speed and cognitive processes such as language ability and intelligence. Due to the questions raised by the unexpected results in the early chapters of this dissertation, I temporarily moved away from the original overall aim. Implications about the need for consistency and shared terminology in the measurement of auditory temporal processing may be used to guide how auditory temporal processing is measured, particularly in relation to other cognitive processes. In the end, the results of these studies lead to a place in which the original questions can be asked again, but with clear ideas, supported by the results of this dissertation, about the important considerations that need to be made moving forward to continue investigating this larger aim.

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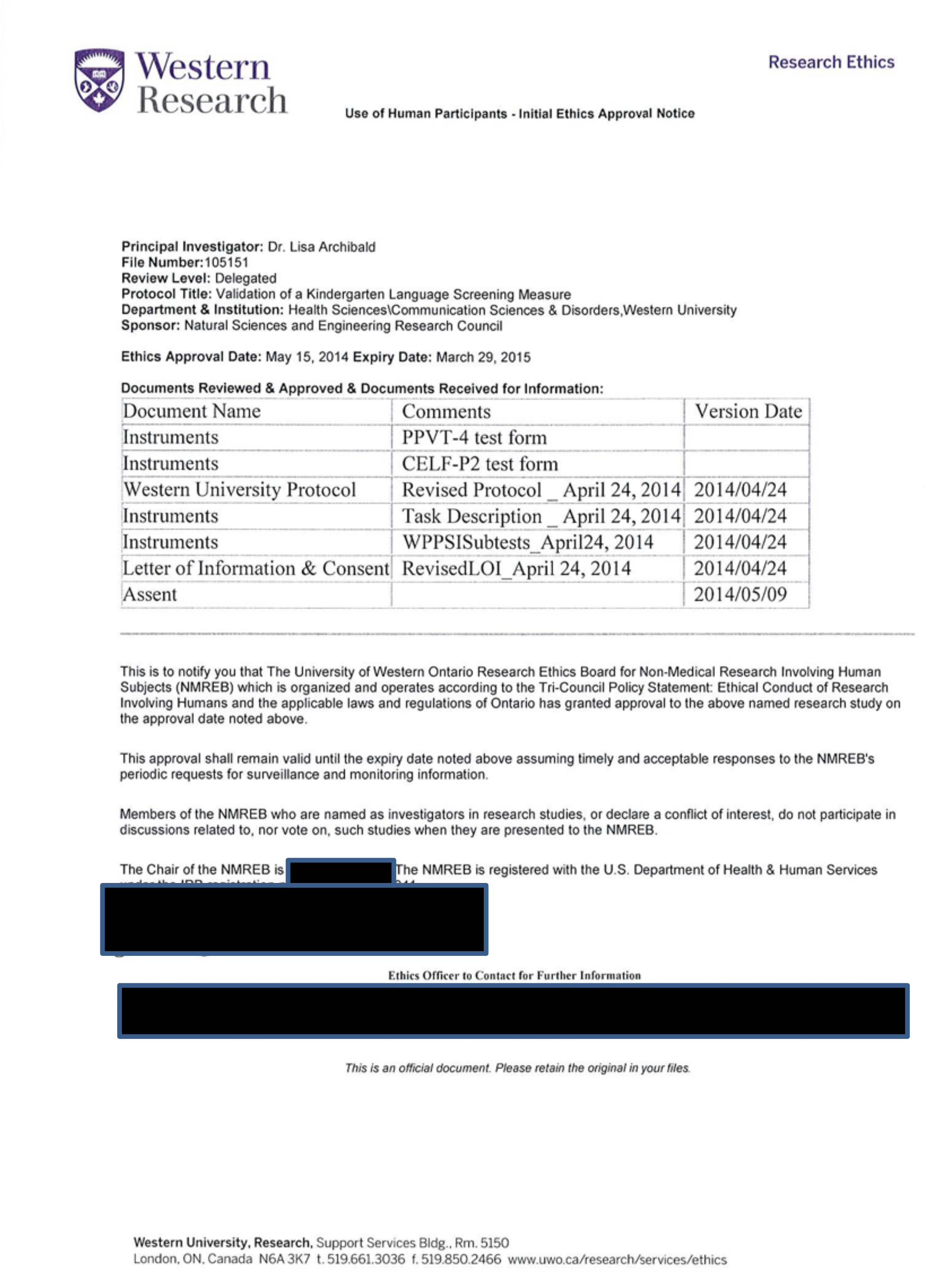
# Appendix A Ethics approval for the study described in Chapter 2



Western Research

Research Ethics

**Use of Human Participants - Initial Ethics Approval Notice**

**Principal Investigator:** Dr. Lisa Archibald
**File Number:** 105151
**Review Level:** Delegated
**Protocol Title:** Validation of a Kindergarten Language Screening Measure
**Department & Institution:** Health Sciences\Communication Sciences & Disorders,Western University
**Sponsor:** Natural Sciences and Engineering Research Council

**Ethics Approval Date:** May 15, 2014 **Expiry Date:** March 29, 2015

**Documents Reviewed & Approved & Documents Received for Information:**

| Document Name | Comments | Version Date |
|---|---|---|
| Instruments | PPVT-4 test form | |
| Instruments | CELF-P2 test form | |
| Western University Protocol | Revised Protocol _ April 24, 2014 | 2014/04/24 |
| Instruments | Task Description _ April 24, 2014 | 2014/04/24 |
| Instruments | WPPSISubtests_April24, 2014 | 2014/04/24 |
| Letter of Information & Consent | RevisedLOI_April 24, 2014 | 2014/04/24 |
| Assent | | 2014/05/09 |

This is to notify you that The University of Western Ontario Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the applicable laws and regulations of Ontario has granted approval to the above named research study on the approval date noted above.

This approval shall remain valid until the expiry date noted above assuming timely and acceptable responses to the NMREB's periodic requests for surveillance and monitoring information.

Members of the NMREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussions related to, nor vote on, such studies when they are presented to the NMREB.

The Chair of the NMREB is [redacted] The NMREB is registered with the U.S. Department of Health & Human Services [redacted]

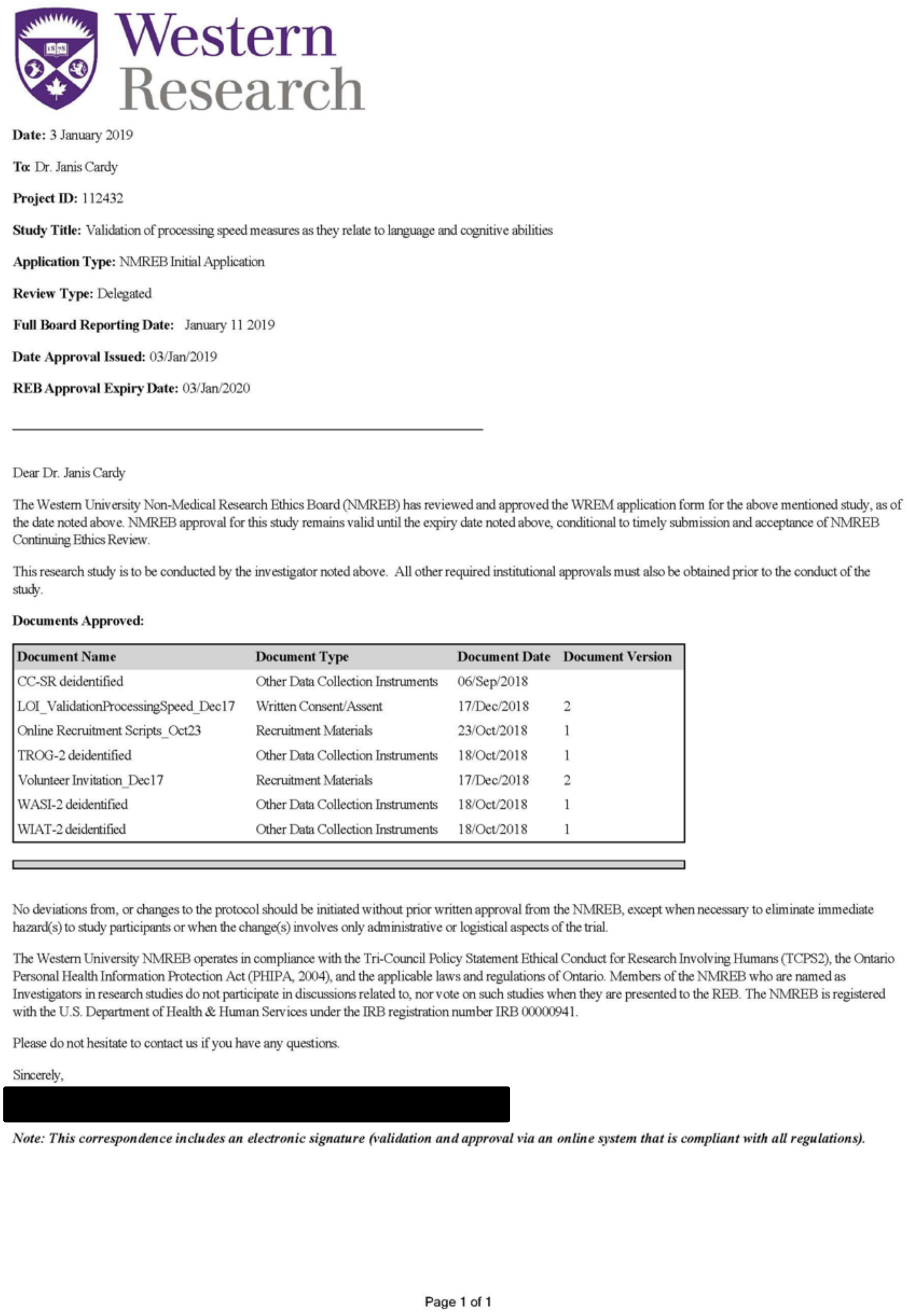
**Ethics Officer to Contact for Further Information**

[redacted]

*This is an official document. Please retain the original in your files.*

**Western University, Research,** Support Services Bldg., Rm. 5150
London, ON, Canada N6A 3K7 t. 519.661.3036 f. 519.850.2466 www.uwo.ca/research/services/ethics

# Appendix B Ethics approval for the study described in Chapter 4



Western
Research

**Date:** 3 January 2019

**To:** Dr. Janis Cardy

**Project ID:** 112432

**Study Title:** Validation of processing speed measures as they relate to language and cognitive abilities

**Application Type:** NMREB Initial Application

**Review Type:** Delegated

**Full Board Reporting Date:** January 11 2019

**Date Approval Issued:** 03/Jan/2019

**REB Approval Expiry Date:** 03/Jan/2020

Dear Dr. Janis Cardy

The Western University Non-Medical Research Ethics Board (NMREB) has reviewed and approved the WREM application form for the above mentioned study, as of the date noted above. NMREB approval for this study remains valid until the expiry date noted above, conditional to timely submission and acceptance of NMREB Continuing Ethics Review.

This research study is to be conducted by the investigator noted above. All other required institutional approvals must also be obtained prior to the conduct of the study.

**Documents Approved:**

| Document Name | Document Type | Document Date | Document Version |
|---|---|---|---|
| CC-SR deidentified | Other Data Collection Instruments | 06/Sep/2018 | |
| LOI_ValidationProcessingSpeed_Dec17 | Written Consent/Assent | 17/Dec/2018 | 2 |
| Online Recruitment Scripts_Oct23 | Recruitment Materials | 23/Oct/2018 | 1 |
| TROG-2 deidentified | Other Data Collection Instruments | 18/Oct/2018 | 1 |
| Volunteer Invitation_Dec17 | Recruitment Materials | 17/Dec/2018 | 2 |
| WASI-2 deidentified | Other Data Collection Instruments | 18/Oct/2018 | 1 |
| WIAT-2 deidentified | Other Data Collection Instruments | 18/Oct/2018 | 1 |

No deviations from, or changes to the protocol should be initiated without prior written approval from the NMREB, except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

The Western University NMREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the Ontario Personal Health Information Protection Act (PHIPA, 2004), and the applicable laws and regulations of Ontario. Members of the NMREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB. The NMREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000941.

Please do not hesitate to contact us if you have any questions.

Sincerely,

[redacted]

*Note: This correspondence includes an electronic signature (validation and approval via an online system that is compliant with all regulations).*

Page 1 of 1

# Curriculum Vitae

Rachael E. Smyth, M.Sc.

## Education

| | |
|---|---|
| In progress | Ph.D. Health and Rehabilitation Sciences, University of Western Ontario,<br>Advisor: Dr. Janis Oram Cardy |
| In progress | M.Cl.Sc. Speech-Language Pathology, University of Western Ontario |
| 2015 | M.Sc. Health and Rehabilitation Sciences, University of Western Ontario,<br>Advisor: Dr. Janis Oram Cardy<br>Thesis: The relation between auditory integration, inspection time and language in children |
| 2012 | B.H.Sc. Health Sciences, University of Western Ontario |

## Honours and Awards

| | |
|---|---|
| Ontario Graduate Scholarship ($15,000) | 2019-2020 |
| Ontario Graduate Scholarship ($15,000) | 2018-2019 |
| Ontario Graduate Scholarship ($15,000) | 2017-2018 |
| Ontario Graduate Scholarship ($15,000) | 2016-2017 |
| FHS Graduate Scholarship Mentoring Program ($1000) | 2016-2017 |
| Achievement in Teaching Excellence Award, University of Western Ontario | 2014 |

## Peer-Reviewed Publications

1. **Smyth, R. E.**, Theurer, J., Archibald, L. M. D., Oram Cardy, J. (2020). Lessons learned in practice-based research: Studying language interventions for young children in the real world. *Autism & Developmental Language Impairment, 5,* 1-14.
2. **Smyth, R. E**., & Ansari, D. (2020). Do infants have a sense of numerosity? A p-curve analysis of infant numerosity discrimination studies. *Developmental Science, 23,* e12897.
3. Searle, M., Kirkpatrick, L. C., **Smyth, R. E.**, & Paolini, M. (2018). Growth in assessment practices: Teacher experiences with summative assessment when working with Grade 7 to 9 students using one-to-one iPads. *Assessment Matters, 12*, 4-33.

4. Kirkpatrick, L. C., Brown, H. M., Searle, M., **Smyth, R. E.,** Ready, E., & Kennedy, K. (2018). The impact of a one-to-one iPad initiative on Grade 7 students' achievement in Language Arts, Mathematics, and Learning Skills. *Computers in the Schools, 35*(3), 171-185.
5. **Smyth, R. E.,** Oram Cardy, J., & Purcell, D. (2017). Testing the accuracy of timing reports in visual timing tasks with a consumer-grade digital camera. *Behavior Research Methods, 49*, 967-971. doi: 10.3758/s13428-016-0757-6
6. Kwok, E. Y., Brown, H. M., **Smyth, R. E**., Oram Cardy, J. (2015). Meta-analysis of receptive and expressive language skills in Autism Spectrum Disorder. *Research in Autism Spectrum Disorders, 9,* 202-222. doi:10.1016/j.rasd.2014.10.008
7. Brown, H. M., Johnson, A. M., **Smyth, R. E.**, & Oram Cardy, J. (2014). Exploring the persuasive writing skills of students with high-functioning Autism Spectrum Disorder. *Research in Autism Spectrum Disorders*, *8*, 1482-1499. doi:10.1016/j.rasd.2014.07.017

## Peer-Reviewed Conference Posters

1. Searle, M., Kirkpatrick L., **Smyth, R.**, Paolini, M., & Brown, H. (2018, October). *Promoting learning through a Collaborative Approach to Evaluation: A retrospective examination of the process and principles.* Evaluation. Cleveland, OH.
2. **Smyth, R. E**., Archibald, L. M. D., Theurer, J., & Oram Cardy, J. (2018, June). *The impact of preschool group language interventions and what predicts success: A retrospective, practice-based study*. Symposium on Research in Child Language Disorders. Madison, WI.
3. Brown, H. M., Trafford, L., **Smyth, R. E.**, Labonte C., Gange, E., Johnson, A. M. Oram Cardy, J. (2018, May). *The challenge of narrative writing for students who struggle to understand the social world*. Development 2018: A Canadian Conference on Developmental Psychology. St. Catharines, ON.
4. Searle, M., Kirkpatrick, L.C., **Smyth, R.,** & Specht, J. (2018, May). *Resource teachers and classrooms teachers teaching collaboratively in regular classrooms: An inquiry.* Canadian Society for Studies in Education. Regina, SK.
5. Kirkpatrick, L.C., Searle, M., **Smyth, R**., & Brown, H. (2018, May). *Students with learning disabilities reading and writing from the Internet: Their cognitive strategies and use of assistive technology*. Canadian Society for Studies in Education. Regina, SK.
6. **Smyth, R.E.**, El-Hayek, N., Archibald, L., Johnson, A.M., & Oram Cardy, J. (2017, June). *Language development and processing speed in young children: A domain general or domain specific relation?* Symposium on Research in Child Language Disorders. Madison, WI.
7. Kirkpatrick, L.C., Searle, M., Brown, H.M., Sauder, A., **Smyth, R. E.,** & Ready, E. (2017, May). *The impact of a 1:1 iPad initiative on intermediate students' language, mathematics, and learning skills achievement*. Canadian Society for Studies in Education. Toronto, ON.
8. Brown, H., **Smyth, R. E.**, Ansari, D. (2017, April). *Which is more? Are dot and digit comparison tasks a strong predictor of children's math abilities? A Meta-Analysis*. Society for Research in Child Development Biennial Meeting. Austin, TX.

9. **Smyth, R. E.,** Oram Cardy, J., Stager, C., DaSilva, M., & Archibald, L. W. M. (2016, June). *Establishing the validity of a kindergarten language screening measure.* Symposium on Research in Child Language Disorders. Madison, WI.
10. Johnson, A. M., Hanna, C., **Smyth, R. E.**, & Whitehead, J. (2016, June). *Leveraging local and online software resources to create engaging learning modules: A case study from the Ontario Online Initiative.* Society for Teaching and Learning in Higher Education. London, ON.
11. Searle, M., Kirkpatrick, L., Sauder, A., Brown, H., Morris, J., Doherty, T., Smiley, E., Henshaw, M., Clow, K., **Smyth, R. E.,** & Ready, E. (2016, May). *Results from the classroom: Understanding educational innovation through the use of a collaborative impact research of a one-to-one device project.* Canadian Society for Studies in Education. Calgary, AB.
12. **Smyth, R. E.,** Johnson, A. M., Purcell, D., & Oram Cardy, J. (2015, July). *Evaluating the validity of an IT task to measure g in children with Specific Language Impairment.* International Society for the Study of Individual Differences. London, ON.
13. **Smyth, R. E.**, Archibald, L., Purcell, D., & Oram Cardy, J. (2015, June). *Auditory temporal integration in children with language impairment compared to age- and language-matched controls.* Symposium on Research in Child Language Disorders. Madison, WI.
14. Kwok, E. Y. L., Archibald, L. M. D., Joanisse, M. F., Nicolson, R., **Smyth, R. E.**, & Oram Cardy, J. (2015, May). *Maturational differences in auditory event-related potentials according to presence versus absence of language impairment in children with autism spectrum disorder*. International Meeting for Autism Research. Salt Lake City, UT.
15. **Smyth, R.E.**, Archibald, L., Purcell, D., & Oram Cardy, J. (2014, June). *No difference in auditory temporal integration between children with language impairment and typical development*. Symposium on Research in Child Language Disorders. Madison, WI.
16. **Smyth, R.E.**, Kwok, E., Brown, H.M., & Oram Cardy, J. (2014, May). *A meta-analysis of receptive and expressive language in Autism Spectrum Disorder (ASD)*. Child Health Symposium. London, ON.
17. Brown, H.M., Oram Cardy, J., **Smyth, R.E.,** & Johnson, A.M. (2014, May). *Exploring the narrative writing skills of students with high-functioning autism spectrum disorders*. International Meeting for Autism Research. Atlanta, GA.
18. Kwok, E., Archibald, L.M.D., Brown, H.M., Joanisse, M., **Smyth, R.E.,** Stothers, M.E., & Cardy, J. (2013, June). *Auditory Temporal Integration (ATI) in children with Specific Language Impairment compared to same age controls.* Canada-Israel Symposium on Brain Plasticity, Learning, and Education. London, ON.

## Professional Experience

**Research Associate** 2017-Present
*Thames Valley District School Board*

**Graduate Research Assistant** 2013-Present
*Autism Spectrum and Language Disorders Lab (Dr. J. Cardy), Communication Sciences and Disorders, Western University*

**Speech-Language Pathology Student Clinician** 2020
*Grand River Hospital*

**Research Assistant** 2013-2019
*Numerical Cognition Lab (Dr. D. Ansari), Department of Psychology, Western University*

**Speech-Language Pathology Student Clinician** 2016, 2017
*H. A. Leeper Speech and Hearing Clinic, London, Ontario*

**Speech-Language Pathology Student Clinician** 2016
*TykeTALK, London, Ontario*

**Online Course Module Developer** 2015
*Health and Rehabilitation Sciences, Western*

**Teaching Assistant** 2013, 2014
*School of Communication Sciences and Disorders, Western*

**Research Coordinator** 2012-2013
*Autism Spectrum and Language Disorders Lab (Dr. J. Cardy), Communication Sciences and Disorders, Western*

**Research Assistant** 2012-2013
*Language and Working Memory Lab (Dr. L. Archibald), Communication Sciences and Disorders, Western*

**Volunteer Research Assistant** 2010-2011
*Department of Hispanic Studies (Dr. J. Bruhn de Garavito), Department of Modern Languages and Literatures, Western*

## Service

**VP Concurrent Degree Representative** 2017-2018
*Health and Rehabilitation Sciences Graduate Student Society, Western University*

**VP External Communications** 2014-2015
*Health and Rehabilitation Sciences Graduate Student Society, Western University*

**Para-Pan Am Games Committee Member** 2014-2015
*Epilepsy Support Centre, London, Ontario*

**Chair - Sponsorship Committee** 2014-2015
*Health and Rehabilitation Sciences (HRS) Graduate Research Conference Committee, Western University*