University of Nevada, Reno

Individual Differences in the Temporal Processing of Neurotypical Children and Adults

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Abstract

Sensory signals from different modalities presented close in time and space are often integrated, building a multisensory perceptual world. A better understanding of the multisensory integration requires characterization of how the nervous system processes time. There are very few studies that have focused on the development and individual variabilities in temporal aspects of sensory processing in neurotypical population. Using a temporal order judgement task (TOJ), this study explored individual differences in the temporal processing of unisensory (auditory, tactile, and visual) and multisensory (auditory-visual, visual-tactile, and auditory-tactile) stimuli in neurotypical children, young adult, and adult. In addition, we examined whether precision of the temporal processing in these TOJ tasks can be influenced by participants' age, intelligence, and sensory responsiveness profiles.

Performance in each of the unisensory TOJ tasks, measured in temporal order threshold (JND) and reaction time (RT) showed significant improvement with age, while the most significant improvement observed in the visual TOJ task. Multiple regression models did not find any significant predictor of JND or RT except for the age. Analysis of multisensory TOJ tasks with a small group of adult participants did not demonstrate any influence of age or task on threshold (JND), point of subjective simultaneity (PSS), or temporal binding window (TBW). However, RTs in the auditory-visual and auditory-tactile tasks were significantly different. TBW in the auditory-visual task and PSS in the auditory-tactile task were significantly predicted by sensory responsive patterns of the participants. In addition, JND comparison between unisensory and multisensory tasks revealed better performance of the adult participants in the unisensory tasks. We conclude (1) temporal order threshold improves with age from childhood to adulthood, and (2) sensory responsiveness pattern, to some extends, predict temporal acuity in the multisensory TOJ task.

Dedication

This work is dedicated to my son, nephews, and nieces- my treasure trove of delightful spirits.

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Chapter 1

Introduction

1.1. General Introduction

In everyday life we are continuously experiencing numerous unisensory cues from the surrounding environment. To get a meaningful gestalt perception of the world around us, it is necessary for relevant unisensory signals to be integrated and at the same time irrelevant signals to be segregated (Spence, 2011). The seamless and coherent combination of sensory inputs from multiple senses, termed as “Multisensory Integration”, provides an enriched presentation of the surrounding (Bremner & Spence, 2008) enabling an appropriate behavioral response to interact with the environment we live in.

Successful integration of stimuli from different modalities requires recognition and discrimination of patterns articulated in time and space (Hirsh & Sherrick, 1961). Individual modalities seem to be specialized in resolving different aspect of stimuli—while the visual system is far better tuned to judge spatial cues of the environment (Howard & Templeton, 1966; Hirsh & Sherrick, 1961) than the tactile or auditory system, whereas the auditory system is tuned better for temporal discrimination of sensory cues (Grondin & Rousseau, 1991; Rousseau et al., 1983). Depending on the spatial or temporal nature in the task requirement, relatively specialized modality takes the upper hand over the other, and this is especially important when stimuli from different modalities come in proximity to each other in time or space (Foss-Feig, 2008).

The temporal information processing or patterning of the incoming sensory stimuli in time to get a meaningful coherent perception (e.g., binding of auditory and visual input in temporal proximity to understand a speech) has been considered to be a crucial aspect of cognitive functioning such as perception, decision making, memory, and motor control (Poppel, 1997; Poppel, 2004; Salthouse, 1996; Szymaszek et al., 2009). Studies have provided evidence of individual differences in temporal processing, depending on the task and complexity of stimuli (Stevenson & Wallace, 2011), mode and order of stimulus presentation (Hillock-Dunn et al., 2012), stimulus duration (Blake & Lee, 2005), and various subject factors such as age, gender, sensory sensitivity, and cognitive abilities (Szelag et al., 2004; Grahn & McAuley, 2009; Szymaszek et al., 2009; Poole et al., 2017).

1.2. Variability in The Temporal Processing Across Sensory Modalities

1.2.1. Auditory Temporal Processing

An age-related decline in auditory temporal processing in adults has been reported in several studies (Fink et al., 2005; Szymaszek et al., 2006; Hirsh, 1959; Hirsh & Sherrick, 1961; Fitzgibbons & Gordon-Salant, 1998). Decrease in cognitive capacities with age also has been widely reported in previous literature (Salthouse, 1996; Park & Schwarz, 2012; Craik & Salthouse, 2011; Salthouse, 1998; Rogers & Fisk, 2001). Szymaszek et al. (2009) studied the relation between age related deficits in cognition and auditory temporal order judgement (TOJ) performances in young and elderly subjects, observing the most significant decline in both variables after the age of 60. According to this study, age induced deterioration in monaural TOJ task threshold, which required attentional shift in space to identify the sequences of stimuli, and cognitive functioning, measured as intellectual and attentional resources, were significantly correlated. Nowak et al. (2016) showed that executive function, an important component of cognition, also decreased with age, which was significantly correlated with the decrease in temporal order threshold of the auditory TOJ task. Szelag et al. (2010) also reported individual variabilities in cognitive capacities in a group of subjects aged 20 to 70 years, and this variation in cognitive abilities could be well predicted by their temporal perception abilities.

While temporal acuity in adult population had been shown to be declined with age, it is suggested to be improved from child to adult (Grose et al., 1993; Irwin et al., 1985; Wightman et al., 1989). Lowe and Campbell (1965) showed that threshold for auditory temporal order judgement is higher (i.e., less precise) in children (7 to 14 years) than adults. Development of temporal resolving power in children, measured in gap detection tasks, showed to be depended on frequency. Some studies suggest for low frequency stimuli (noise) this development continues above the age of ten while for high frequency, the development reaches the adult level by the age of six (Grose et al.,1993; Irwin et al.,1985). Wightman et al. (1989) (3-7, and adult) suggested the development of temporal resolution for both high and low frequency that continues beyond age six.

1.2.2. Visual Temporal Processing

Despite our limitations to imagine a visual world that could be different from the one we personally live, studies have shown accountable inter-individual differences in visual perception of neuro-typical subjects. Halpern et al. (1999) demonstrated a two-fold difference between the best and the worst performance of their young adult subjects in the contrast sensitivity and wave-length discrimination tasks and a tenfold difference in Vernier acuity measurement. This study also showed remarkable variability in the overall visual performance of the subjects, in addition to the difference in individual tasks. Ward et al. (2017) reported four to five times variations in visual TOJ task performance in a large study group of young and older adults.

Busey et al. (2010) showed the changes in visual TOJ task performance with age, and their association with participants' sensory and cognitive abilities. Implementing different TOJ tasks (two/four items in same/different location) in a study group of 261 (aged from 18 to 88 years), they demonstrated higher threshold in all the tasks for the older subjects compared to the young subjects. To further investigate the relation between the performance of the elders and their sensory and cognitive ability, this study applied Wechsler Adult Intelligence Scale III (WAIS-III) and measures of temporal information processing (e.g., temporal contrast, letter contrast, and gap detection). They found the information processing speed and letter contrast sensitivity as two significant predictors of the TOJ performance.

Baltes and Lindenberger (1997) conducted a study in an adult large study group (age 25 to 103yr, 687 participants) to examine the magnitude of correlation between sensory functions (e.g., visual, and auditory acuity) and cognitive abilities (processing speed, memory, reasoning, knowledge, and word fluency). While they established that both the sensory and cognition functions show significant age-related declines, individual differences in cognitive abilities could be well predicted by individual differences in vision and audition. More interestingly, these shared variance between intellectual abilities and visual and/or auditory acuity are much higher in the group of 70 to 103 years than the age group of 25 to 65 years, suggesting that the connection between the sensory and cognitive functioning was present throughout the adult life but was intensified in old age.

Ulbritch et al. (2009) studied effects of age, sex, and cognitive factors on visual and auditory TOJ performance in an adult and elderly subject group. They supported previous findings that performance in TOJ tasks deteriorates with age, with significant increase of Temporal Order Threshold (TOT). This study found that cognitive functions of the participants, including fluid reasoning, attention, and short-term memory, were more significant and consistent predictors of their performance in most of the TOJ functions than their age and gender. In addition, these cognitive functioning measures alone were suggested to be accountable for most of the age-related changes in TOJ task of the participants. Apart from the cognition, age was also a significant predictor of visual TOJ task performance, indicating age related sensory deficits also account for TOT variance.

1.2.3. Tactile Temporal Processing

In accordance with the findings of other two sensory modalities, temporal information processing in tactile sensation also decreases with age (Craig, 2010; Laasonen, 2001; Verrilo, 1993; Humes et al., 2009). Sensory thresholds in all major senses, including vision, audition, and tactile, have been shown to increase with the advanced age (International Standards Organization [ISO], 2000, for hearing; Kim & Mayer, 1994, and Owsley et al., 1983; for vision; Gescheider et al., 1994; Verrillo & Verrillo, 1985 for tactile). Humes et al. (2009) studied visual, auditory, and tactile temporal sensitivity in a large study group of young and older subjects and reported that mean threshold value for the older subjects were significantly higher than the younger subjects. Stevens et al. (1998) also showed detection thresholds in multiple senses, including hearing, tactile, and temperature, increased with the age of the subjects. This study also reported significant positive correlation between performance in these detection tasks and cognitive abilities of the participants. Poole et al. (2015) investigated the relationship between tactile temporal separation thresholds and Autism spectrum quotient (AQ) in an adult non-clinical population. They found that these self-reported AQ scores were positively correlated with their tactile thresholds, suggesting participants who had higher autistic traits tended to show lower precision in tactile temporal separation tasks.

1.3. Multisensory Integration

1.3.1. Principles and Variability with Age

Coherent binding of relevant sensory information into multisensory representation significantly changes behavioral and perceptual process (Stein et al., 2010). Researchers have been continuing to study and establish the principles of the multisensory integration in both neuro-typical and neurological conditions. Multisensory facilitation is one of these principles, stating that temporally and spatially coherent sensory signals provide beneficial perceptual and behavioral qualities. Studies have provided evidence of multisensory facilitation in terms of better detection (Lovelace et al., 2003; Stein & Wallace, 1996) and localization (Nelson et al., 1998; Wilkinson et al., 1996) of stimuli, and faster reactions to the stimuli (Miller, 1982; Diederich and Colonius, 2004; Hershenson, 1962).

Multisensory integration often involves dominance of one modality over the other. Depending on the temporal or spatial nature of the task, the relatively more specialized modality overrides the processing of other modalities (Robinson et al., 2018; Foss-Feig, 2008). While there is a robust evidence in favor of the visual dominance over audition, tactile and proprioception when spatial resolution of sensory input is required (Colavita, 1974; Posner et al., 1976; Pick et al., 1969), audition has been suggested to be dominating in tasks where resolving the temporal input is required (Hirsh, 1952; Pieron, 1952). Interestingly, it has been suggested that sensory dominance changes from childhood to adulthood, with children showing dominance of audition over vision in detection task and temporal sensitivity task (e.g., sound induced flush illusion task) (Barnhart et al., 2018; Nava and Pavani, 2013). In addition, these studies suggested that stimulus onset asynchrony also influenced the dominance, with the modality engaging the processing first dominated.

“The law of prior entry” stated by Titchener in 1908, which focused on the effect of attention on sensory processing, is another important issue in multisensory processing. Prior studies (Titchener, 1908; James, 1890; Posner et al., 1978) suggested that attended stimuli are more readily perceived than simultaneous, but non-attended stimuli. Spence et al. (2001), using visual-tactile TOJ paradigms in adult neurotypical (NT) population, reported attentional bias towards the visual cue and towards the right side of the space in spatial location discrimination tasks. Their finding that more tactile or left leading stimulus would be required to perceive synchrony in the TOJ tasks provided evidence for this theory.

Temporal sensitivity or ability to discriminate between sensory signals from multiple modalities in time appears to be changing across lifespan in NT population (Hillock-Dunn et al., 2011; Hillock-Dunn & Wallace, 2012; Baum & Stevenson, 2017; Bedard & Barnett-Cowan, 2016). The time interval within which temporally approximate sensory stimuli from different modalities bind together to provide a gestalt perception, is termed as "Temporal Binding Window" (TBW, Baum & Stevenson, 2017). One of the most studied aspects of multisensory integration is the audio-visual TBW, which is evidently disrupted in neurodevelopmental disorders such as Autism Spectrum Disorder (ASD), dyslexia, and schizophrenia. Individuals with these conditions showed poorer performance in judging the temporal order of auditory and visual stimuli, as indicated by wider TBW and higher threshold than their typically developing peers (Stevenson et al., 2014; Stevenson & Wallace, 2011; Noel et al., 2018; Virsu et al., 2003; Laasonen et al., 2001).

It has been shown that there is significant individual variability in the TBW span even in neurotypicals. The size of the TBW is dependent on the age of the subject, stimulus type, stimulus presentation order, and complexity of the task used to estimate the window (Powers et al., 2009; Stevenson & Wallace, 2013; Dixon & Spitz, 1980). Hillock-Dunn et al. (2012) investigated multisensory TBW in a NT study group ranging from 6 to 23 years of age. Using an audio-visual simultaneity judgement task, they showed that children (6 to 11years) and adolescent (12 to 17 years) were less sensitive to the audio-visual asynchrony, with larger temporal binding window than that of the oldest group (18 to 23 years). They concluded that temporal processing of multisensory stimuli matures with age as expected, however this maturation process occurs over an elongated period extending into the adolescence. In their study age alone was accountable for approximate 20% of the variance in the size of temporal binding window, although they did not find any significant correlation between TBW size and verbal IQ, non-verbal IQ, and reading ability of the participants. Zhou et al. (2020) suggested that the development of audio-visual TBW shows a U-shaped pattern, decreasing in size and reaching the maturity in late adolescence and starting to increase in size in late adulthood.

Perceptual synchrony is measured as the Point of Subjective Simultaneity (PSS), denoting the stimulus onset asynchrony between two stimuli at which they are perceived to be simultaneous (Stone, 2001; Chen et al; 2020). While TBW was evidently deteriorates in adults with advancing age ((Baum & Stevenson, 2017; Brooks et al., 2018; Setti et al., 2011a; Stevenson et al., 2018), perceptual synchrony between stimuli has not been affected by age significantly (Bedard & Barnett-Cowan, 2016; Scurry et al., 2019; de Boer-Schellekens & Vroomen, 2014). A recent study (Chen et al., 2020) though reported that precision in audio-visual simultaneity judgement deteriorates in middle aged and older adults compared to their younger counterparts, with bias towards the auditory cues (i.e., shift of PSS towards the visual leading).

1.3.2. Multisensory Integration and Cognitive ability/Sensory sensitivity

Zhou et al. (2020) showed that the neurotypical children and adolescents with higher level of atypical sensory responsiveness (hypersensitivity, hyposensitivity, or avoidance, measured by Adult/Adolescent Sensory profile) have reduced temporal acuity in visual TOJ task. This study did not find the participants’ auditory and audio-visual temporal acuity to be related to their sensory profile. Barutchu et al. (2011) investigated the relationship between the multisensory integration and intellectual ability in a group of 88 children (mean age: 9.7 years). Using an audiovisual detection task in quiet or noisy auditory background, this study demonstrated that children who showed stable performance (motor reaction time and accuracy) in both quiet and noisy conditions also showed superior performance in full scale of the Wechsler Intelligence Scale for Children IV (WISC-IV). Participants who performed poorly (larger reaction time, and/or higher error rate) in the noisy condition showed below average verbal comprehension ability. On the other hand, participants with poor performance in the quiet condition showed lower scores in Perceptual Reasoning Index (PRI), an index reflecting their ability of problem solving and reasoning. Rammsayer and Brandler (2007) also suggested performance in the audio-visual TOJ task is positively correlated to general intelligence of the participants measured as the “psychometric g”. The psychometric g comprises of a wide range of intelligence tests including verbal comprehension, processing speed, memory, and reasoning; a higher score in this measure implies a better temporal resolution.

Poole et al. (2017) investigated cross-modal temporal acuity of adult autistic group and their age matched controls, using auditory-visual (AV), auditory-tactile (AT), and tactile-visual (TV) TOJ tasks. This study did not find worse cross-modal temporal acuity for the autistic individuals than their neurotypical controls. However, it did report an overall significant correlation between the participants’ temporal acuity and their sensory sensitivity (measured by Glasgow Sensory Quotient/GSQ). For both groups, participants who showed reduced temporal acuity in the tactile-visual conditions reported higher sensory sensitivity. Also subjects who showed bias towards the visual cue in the auditory-visual tasks (i.e., needed more auditory lead to perceive those as simultaneous), reported greater atypical sensory responses.

1.4. Variability in Reaction Time

Reaction time has been used as an indicator of cognitive capability in many studies and has been a favorite subject of experimental psychology to explore. Reaction time is often influenced by the type of experiment, type of stimulus, stimulus intensity, and subjective factors. Both simple reaction time (SRT) in detection tasks and choice reaction time (CRT) in TOJ tasks slow with advancing age. While SRT does not show significant increases until the age around 50 years, CRT increases throughout the adult age with increase in the intrasubject variability (Der & Deary, 2006). Several studies suggest that children show slower processing in different cognitive processing tasks, including choice reaction tasks, evident by the higher reaction time with larger variability, in comparison to adults and young adults (Goldberg et al., 2001; Hale, 1990; Wiersema et al., 2007, Van Damme & Crombez, 2009). Interestingly, reaction time for adults to visual stimuli was found to be larger than that to auditory stimuli, as shown in different TOJ and simple reaction time tasks (Chocholle, 1940; Jaskowski et al., 1990; Neumann et al., 1964).

Baratchu et al. (2009) examined the correlation between mean RT in simple auditory, visual, and audio-visual detection tasks in children with their non-verbal IQ and reading ability. They found only a weak positive association of the non-verbal IQ with the mean response time in the unisensory tasks, but interestingly, not with the mean RT of multisensory task. Deary et al. (2000) examined the relationship between the general mental ability of an adult population (measured by Alice Heim 4/AH4 test including verbal, numerical, and total test scores) and their choice reaction time and reported strong negative correlation between participants' intelligence and reaction time.

1.5. Theories for varied Temporal Order Threshold across TOJ

Theories have been proposed to explain the threshold in determining temporal order of two sensory stimuli, including the central timing theory and feature specific theory (Ulbritch at el., 2009; Allman & Meck, 2012). The central timing theory is based on the findings in the early works studying perceived temporal order of different sensory stimuli. Poppel (1997) proposed the concept of the "Neuronal Oscillation Phase", evoked by one stimulus, and suggested that two stimuli occurring within this phase would be perceived as synchronous. The minimum temporal gap that is required to judge the order of stimuli presented, is independent of the sensory modality involved and the quality of the stimuli. This gap is reported to be 20 to 40 ms (Hirsh, 1959; Hirsh & Sherrick, 1961; Poppel, 1997; Kanabus et al., 2002). On the contrary, the "Feature Specific Processing" theory suggests the temporal order threshold would widely vary according to the modality and stimulus type, as different neuronal mechanisms are involved in the processing of temporal succession of two stimuli (Fink et al., 2005; McFarland et al., 1998).

1.6. Common cause hypothesis: Interrelation between cognitive function and sensory function

The shared variance in cognition and sensory/sensory motor function, and its intensification from adult to old and very old subject group is widely reported in literature

(Baltes et al., 1997; Anstey et al., 2001; Lindeberger et al., 1994, Salthouse, 1996; Stevens, 1998). Common Cause hypothesis (Baltes & Lindenberger, 1997; Salthouse, 1996; Craig et al., 2010) suggested that the relation between cognitive and sensory function in old age is the outcome of aging induced changes in both brain structure and functional integrity. Salthouse (1996) suggested this common factor indicates an "overall reduction in the central nervous system functioning" with age.

Processing speed theory (Fitzgibbons & Gordon-Salant, 1998; Salthouse, 1996) suggests the speed of information processing decrease with advancing age, which may result in inefficient integration of relevant information within the "limited time" frame or disrupt the simultaneous integration of necessary information for a successful cognition. While studies involving young adult, adult, and elderly subject groups showed profound individual differences in such declines, the most significant declines in cognition and in TIP reportedly started at 6th or 7th decade of life (Szymaszek, 2009), although Salthouse (2009) reported some aspects of cognitive aging (e.g., matrix reasoning, spatial visualization, and processing speed) could start at as early as 2nd or 3rd decade of life.

1.7. Current Study

Studies have provided evidence of individual differences in unisensory and multisensory temporal processing in both neurotypical and atypical population. However, there had been very few studies systematically examining temporal processing in multiple modalities within the same study group (Humes et al., 2009). In addition, these studies had focused mostly on the aging effect on the different aspects of sensory processing of adult and older subjects (e.g., Stevens et. al., 1998) or to evaluate the sensory responsiveness pattern associated with behavioral response of a diagnostic/clinical group such as children with ASD (e.g., Feldman et al., 2018). The current study proposed to fill this gap by examining whether there are individual differences in auditory, visual, and tactile temporal processing in a neurotypical group of subjects age ranged 8 to 25years. Individual difference studies are useful in the "exploratory analysis" (Thurstone, 1944; 1947). Studies exploring individual differences of perception would be useful in establishing its nature and causation by demonstrating relation or non-relation of variables and by defining the common predictors of perception (Wilmer, 2008).

Both temporal order judgement (TOJ) and simultaneity judgement (SJ) tasks have been used successfully in studies to determine temporal information processing capability of the participants across different modalities (Stone et al., 2001; Vroomen et al., 2004; Spence et al., 2001; Cardoso-Leite et al., 2007). However, SJ task can produce response bias as subject could have strong inclination to judge stimuli presented in close proximity as simultaneous. (Poole, 2017). Using both unisensory and multisensory TOJ tasks, the current study intended to explore individual differences in the temporal information processing in typically developing children and young adults. In addition, we intended to determine whether the temporal processing ability of the participants can be predicted by their age, IQ, and sensory responsiveness patterns.

Research questions:

1. Do the children and young adults have the same level of sensitivity in their sensory temporal processing?

While studies mostly focused on the individual variability in the auditory, visual, and audio-visual temporal processing tasks, this study aimed to study variability in TOJ performance within and across three major sensory modalities. Study of auditory, visual, and tactile temporal perception in the same study group would give us a better understanding of unisensory temporal processing which is important for multisensory integration. This study focused on both the children and young adults' temporal processing ability, providing insights on the development of temporal perception from childhood to adult life.

Null hypothesis: There would be no effect of age on the performance of children and adult in the unisensory and multisensory TOJ tasks.

Alternative hypothesis: Age of the participants would have an effect on their performance in the unisensory and multisensory TOJ tasks, with adults performing better than children.

2. Do the cognitive capability and sensory profile predict the perceptual ability of the children and adult?

Existing studies suggested temporal information processing varies with cognitive ability and patterns of sensory responsiveness of the subjects, in addition to their age (Szelag at el., 2004; Szymaszek at el., 2009; Poole at el., 2017 Barutchu et al., 2010; Zhou et al., 2020). This study aimed to explore whether sensory responsiveness patterns (sensitivity/hypersensitivity, hyposensitivity/low registration, sensory seeking, and sensory avoiding), and IQ profiles in the neurotypical children and adult participants are associated with their temporal information processing ability.

Null Hypothesis: Cognitive capability and sensory responsiveness of the children and young adults would not predict their performance in the unisensory and multisensory TOJ tasks.

Alternative hypothesis: Cognitive capability and sensory responsiveness of the children and young adults would predict their performance in the unisensory and multisensory TOJ tasks.

Chapter 2

Methods and Materials

2.1. Participants

Total of 55 participants were recruited from the University of Nevada, Reno, and the surrounding areas for this study. One participant did not pass the visual screening and another participant did not pass the auditory one. Seven participants did not complete the study, and their data were therefore excluded from the analysis. 46 Participants completed the unisensory TOJ tasks (age range of 8-25 years; gender: 13 male and 33 female), 45 of them completed the cognitive task, and 44 of them completed the sensory profile. 15 of the 46 participants, within the age range of 20-25 years (2 male and 13 female), additionally participated in the multisensory TOJ tasks. Participants completed the study in one or two visits, one session per visit.

All Participants reported normal or corrected to normal vision and normal hearing, all were right- handed (self-reported), except for one subject. Participants were screened for visual acuity and were required to have 20/25 vision (with correction). Participants were also screened for hearing and were required to have a pure tone threshold lower than 25 dB for 1 and 2 kHz. Participants with psychiatric/neurological disorder, history of epilepsy, brain trauma or surgery, or taking anxiety/depression medication were excluded from the study. Participants (or their guardians) provided signed informed consent before any experimentation and were financially compensated for their time. The protocol was reviewed and approved by the Institutional Review Board at the University of Nevada, Reno.

2.2. Cognitive & Sensory Functioning Assessment

A. Wechsler Abbreviated Scale of Intelligence (WASI, 1999)

WASI was administered to evaluate the intellectual functioning of all the participants. WASI is a brief, but standardized tool for rapid evaluation of general cognitive ability, applicable for the participants between 6 to 89 years old, which made it useful to use for research and educational settings (Wechsler,1999). It has four subsets - Vocabulary, Matrix reasoning, Block design, and Similarities, to evaluate verbal intelligent quotient (IQ) (including vocabulary and similarities sections), performance IQ (including matrix reasoning and block design sections) and full-scale IQ (including all four sections). These subtests in this test are equivalent to those in WISC-III (6-16yr) and WAIS-IV (16-90yr) test, only that WASI is applicable for a wide range of age group, which made it appropriate for our study.

B. SHORT Sensory Profile 2; Caregiver questionnaire

This sensory profile is applicable for children aged 3 to 14.11 years and provides rapid and reliable assessment of the child's sensory perception, making it suitable to use for screening and research purposes (Dunn, 2014). It includes a list of questions using Likert scale about the sensory processing of the child in the context of their daily life (e.g., "is distracted when there is a lot of noise around) and their "behavioral response" associated with these processing (e.g., "struggles to pay attention"). We used this profile for our participants aged from 8 to 14 years, completed by their parents/caregivers.

C. Adolescent/Adult sensory Profile

This sensory profile (by Brown and Dunn, 2002) is applicable for individuals that are 11years or older. This profile provides a quick, but reliable assessment of an individual's sensory processing as it focuses on their general behavioral responses to daily life's sensory experiences. This profile includes a list of Likert questions regarding individuals' behavior/ activity preferences to different sensations including vision, audition, touch etc. As this profile is congruous with profile of the kids, it would be beneficial for this study to assess how individuals with different ages resemble or differ from each other in their sensation (Technical Report: Adolescent/Adult sensory profile, 2014). We used this for our participants from 15 to 25 years old and they completed the profile themselves.

2.3. Behavioral Assessment

2.3.1. General Procedures

In the test sessions, each of the three unisensory TOJ tasks- auditory, visual, and tactile were divided into four blocks with each block lasting five to eight minutes, allowing participants to take self-paced breaks in between blocks. Each block had 115 trials, total 460 trials for each task. Stimulus Onset asynchrony (SOA), defined as the time gap between the onset of first stimulus and the onset of the second stimulus, varied between +400ms to -400ms at 23 levels (±400ms, ±350ms, ±300ms, ±250ms, ±200ms, ±150ms, ±75ms, ±50ms, ±35ms, ±20ms, ±10ms, and 0ms). Positive SOAs indicated that the stimulus presented to the right was leading, while negative SOAs indicated that the stimulus presented to the left was leading. 0ms SOA indicated that the stimuli presented to the right and left were simultaneous. Each SOA was repeated five times in each block at random order. Task order were randomized for the participants. Note that before each unisensory TOJ task, participants were given a practice session of 24 trials (3 trials x 8 stimuli -SOAs: ±250, ±200, ±150, ±100ms) with feedback.

For the multisensory TOJ tasks, participants performed a practice session of 12 trials (2 trials x 6 SOAs: ±600, ±550, and ±450ms), before each task, with feedback. In the test sessions, each task was divided into five blocks, allowing the participants to take self- paced breaks between blocks. Each block consisted of 110 trials, resulting a total of 550 trials for each task. SOAs varied from +600ms to -600ms, divided into three groups: short SOAs (±400, ±350, ±300, ±250, ±200, ±150, ±75, ±50, ±35, ±20, ±10 and 0 ms), each level was repeated 4 times; medium SOA (±450ms) which was repeated three times, and large SOAs (±500, ±550, ±600 ms), each SOA level was repeated two times. Positive SOAs represented auditory leading stimuli in auditory-visual task and tactile leading stimuli in both visual-tactile and auditory-tactile tasks. 0 ms SOA indicated that stimuli were simultaneous. Task order was randomized for each block.

SOA levels had been selected for the TOJ tasks based on previous literature (Baum et. al., 2015) and pilot testing. For each task, subjects were positioned 60cm from the computer screen. They were instructed to fixate on a fixation cross on the computer screen, press any key to start, and give their responses as rapidly as possible after the stimuli were presented. There were also instructions on the display asking participants to press corresponding keys/pedals to give response. Next trial started with a 1.5 second after participants had given their responses.

For the evaluation of the children and adults' pattern of sensory responsiveness, two different but congruous sensory profiles were used and the raw scores in the profile transformed into Z-score for standardization. To evaluate participants' cognitive capabilities, Wechsler's Abbreviated Scale intelligence (WASI) was implemented. This scale has standardized T-score and percentiles for both child and adult participants based on the raw scores from different subsets. The current study included full scale IQ percentile and performance IQ percentile for each subject as their cognitive variable.

2.3.2. Apparatus and Stimuli

Auditory TOJ: Two auditory stimuli of same frequency (1khz pure tone) and volume (25dB) were presented via noise cancelling headphone to the right and left ear at different SOAs. Participants were asked to press left arrow if the left sound first, right arrow if the right sound came first, using their dominant hand. Auditory stimuli were delivered through an Audiofile stimulus processor (Cambridge Research Systems, Rochester, UK).

Visual TOJ: Visual stimuli were generated using MATLAB (MathWorks, Natick, MA, USA) with Psychtoolbox extensions (Pelli, 1997; Brainard, 1997) and were delivered through a Display++ LCD monitor. Visual stimuli were a pair of white circles with a diameter of 3.2° presented on a grey background for 50ms in a dim lit room. They were presented on each side of the fixation cross at 15.94° visual angle, with different SOAs between the two circles. Participants were instructed to press left arrow if left stimulus came first and right arrow if right came first with the index finger of their dominant hand. Participants were positioned 60 cm in front of the computer screen and a chin rest was used to minimize their head movements.

Tactile TOJ: Tactile stimuli were mechanical vibrations delivered by a non-invasive tactile device from Engineering acoustic Inc (EAI). Two vibrations at 50Hz frequency were delivered to index finger of right and left hand for 50ms duration, at different SOAs between the two vibrations. Participants were instructed to provide response as soon as possible by pressing left pedal if left stimulus came first and right pedal for the right first using their dominant foot.

Multisensory TOJ: Three pairs of bimodal TOJ tasks were applied to evaluate multisensory integration: auditory-visual, visual-tactile, and auditory-tactile. Auditory, visual, and tactile stimuli were same as the ones used in the unisensory tasks described above. Participants were asked to determine the temporal order between stimuli from two modalities, presented bilaterally/ binaurally/ bimanually, and respond with their dominant hand (for auditory-visual task) or foot (for visual-tactile and auditory-tactile task) as rapidly as possible.

Chapter 3

Data analysis and Results

3.1. Data analysis:

Participant’s responses in the temporal order judgement tasks were recorded along with the response time and were plotted as a function of SOAs. Response plotted depended on the task: proportion of “right first” responses for three unisensory TOJ tasks; proportion of “tactile first” responses for the auditory-tactile task and tactile-visual task, and proportion of “audio first” response for auditory-visual task. Individual data then fitted to a Normal cumulative distribution function (CDF) (Fechner, 1860; Burr et al., 2009). SOA which corresponds with the 50% on the y-axis of the cumulative distribution represents Point of Subjective Simultaneity or PSS (Figure 1). PSS is the measure of participants synchronous perception of stimuli from different senses and bias in the judgement of their temporal order. Another estimate termed as Just noticeable difference (JND) or “threshold of difference” was obtained from the distribution (Figure 1), which is the standard deviation of the distribution and represents the minimum temporal difference between stimuli which the subject can detect. Standard errors were estimated by bootstrapping method for both PSS and JND measures. In addition, temporal binding window (TBW) was evaluated for multisensory tasks, representing span of time within which stimuli from different modalities are integrated and bound to form a perceptual event (Wallace & Stevenson, 2014). TBW was calculated by summing up the absolute values of threshold for 25% and threshold for 75% “audio first” (audio-visual TOJ task) or “tactile first” (visual-tactile and audio-tactile TOJ tasks).

Response time for each trial was recorded as the time between the disappearance of the fixation and pressing the corresponding response key or pedal (in the TOJ tasks that involving tactile stimuli). For each task, response time was averaged across SOA levels to obtain an average response time for each participant.

For Unisensory tasks, data from 40 subjects were included in the JND and Reaction Time (RT) analysis. Data from six subjects were excluded as either their performance could not yield an expected level of 75% accuracy or their JND exceeded the maximum level of SOAs used in the task. After checking the normality assumptions of the dependent variable, two separate ANCOVAs were conducted for JND and RT with Age as a continuous independent variable and Task (Levels: auditory, visual, and tactile) as a categorical independent variable.

For the Multisensory Tasks, data from 13 subjects within the age range of 20 to 25 years were analyzed and JND, PSS, TBW, and RT in each task were obtained. Data from two subjects were excluded as their JND exceeded the maximum level of SOA used in the task. Four separate one-way ANOVAs were run with JND/PSS/TBW/RT as dependent variable and Task (Levels: auditory-visual/AV, visual-tactile/VT, and auditory-tactile/AT) as the independent categorical variable.

Studies exploring individual differences in metrices of sensory perception have used correlation and linear regression models to determine their associations and their predictors (e.g., Stevenson et al., 2012; Zmigrod & Zmigrod, 2016; Cecere et al., 2015; Venskus & Hughes, 2021). The current study applied similar correlation analysis and simple and multiple linear regression models to explore individual differences in temporal processing among neurotypical children and adults.

3.2. Results

3.2.1. Unisensory TOJ Task Analyses

Figure 2 shows mean JND values (2A), and mean response time (RT) (2B) for the auditory, visual, and tactile TOJ tasks. Estimated marginal mean of JND for visual TOJ task is 47.5 ± 71.37 ms, while mean JND for auditory and tactile tasks are 136 ± 68.38 ms and 130.8 ± 79.88 ms, respectively. Estimated marginal mean of the response time for the visual task is 315 ± 191.82 ms, estimated marginal mean for tactile task is 641 ± 401.46 ms and for the auditory tasks is 459 ± 323.29ms.

3.2.1.1. ANCOVA results

ANCOVA (dependent variable: JND; continuous independent variable: Age; categorical independent variable: Task with 3 levels: auditory, tactile, and visual) showed significant main effect of age ($F(1,40) = 37.23$, $p<0.001$, partial $\eta 2=0.24$) and task ($F(2,40) =5.79$, $p =0.004$, partial $\eta 2=0.29$). There was no significant interaction between age and task ($F(2,40) = 1.49$, $p=0.23$, partial $\eta 2=0.026$). Tukey's pairwise post-hoc analysis showed significant JND difference between auditory and visual ($p <0.001$), between visual and tactile ($p <.001$), but not between tactile and auditory task ($p=0.93$). Linear regression line for JND in each TOJ tasks showed decline of JND with age (auditory task: β -0.53, $p<0.001$; visual task: β -0.33, $p<0.05$; tactile task: β -0.61, $p<0.001$) (Figure 3).

RT was transformed into log value to obtain a normalized distribution of the values. ANCOVA was conducted, with log transformed RT as dependent variable, Age as continuous independent variable and Task as categorical independent variable. As in the case of JND, age (F (1,40) = 96, p <0.001, η2=0.45) and task (F (2,40) = 24.65, p <0.001, η2=0.30) showed significant main effect on the mean RT, although there was no interaction between age and task (F (2,40) = 0.36, p= 0.70, η2=0.006). Tukey's HSD post-hoc analysis showed mean difference was significant for all three comparisons (between auditory and tactile task: p<0.001; between visual and tactile task: p<0.001; and between auditory and visual task: p <0.01).

3.2.1.2. Pearson's Correlation Between Dependent Variables

Pearson's Correlation between dependent variables (JND/RT) in three unisensory TOJ tasks were analyzed, and results are summarized in Table 1. Significant correlation was found between JND in the tactile and auditory task (r(38) =.68, p <.01), between tactile and visual task (r(38) = .65, p <.01), and between visual and auditory task (r(38) = .40, p <.05) (Table 1A). Response time in each task was significantly correlated with each other (ps <.001) (Table 1B).

3.2.1.3. Multiple Linear Regression

Multiple regression models were conducted with Age, Sensory profile, and IQ profiles to predict JND and RT in each unisensory TOJ task, using data from the subjects (37) who had completed all the TOJ tasks, sensory profile, and WASI. Since two different sensory profiles have been used (Short sensory profile: 8 to 14 years old, Adult/Adolescent Sensory Profile: 15 to 25 years old), raw scores from these two profiles were standardized to Z- scores and used in the analysis. Regression model was found significant for JND in tactile task (adjusted R^2 =0.41, F (7,29) = 4.59, p= 0.001), with age being the only significant predictor with regression weight (β) of -0.70 (p<0.001); and for

JND in visual task (adjusted $R^2 = 0.24$, $F(7,29) = 2.64$, $p<0.05$) with age (β -0.46, $p<0.01$) and low registration of sensory profile (β -0.43, $p<0.05$) being the significant predictors. Age also significantly predicted JND in the auditory task (β -0.60, $p<0.001$), though the regression model was not significant itself (adjusted $R^2= 0.18$, $F(7,29) = 2.16$, $p>0.05$).

For reaction time, regression model was found significant in auditory task (adjusted $R^2=0.41$, $F(7,29)=4.62$, $p=0.001$) with age being the only significant predictor (β -0.65, $p<0.001$), in visual task (adjusted $R^2 = 0.39$, $F(7,29)=4.25$, $p<0.01$) with age again being the only significant contributor (β -0.62, $p<0.001$), and in tactile task (adjusted $R^2=0.59$, $F(7,29)=8.26$, $P<0.001$) with both age (β -0.77 , $p<0.001$) and performance percentile IQ (β 0.52, $p<.05$) contributing significantly to this model.

Follow-up correlation test did not show significant correlation between JND in the visual task and low registration sensory pattern ($p >0.05$) or between response time in tactile task and performance IQ percentile ($p> 0.05$). Scatterplot for visual JND and low registration sensory score (Z score) showed a few outliers with higher score in JND with relatively low sensory pattern score (Figure 4A). Similarly, scatterplot for the reaction time in tactile task and performance IQ percentile showed outliers with high IQ percentile and high reaction time (Figure 4B).

Another set of multiple regressions were conducted to predict JND, and RT obtained in three TOJ tasks from the age and IQ profiles (without Sensory profiles) with data from 39 subjects. Similar to the results described above, significant regression equation was found for each model, with age being the only significant predictor of JND (see Figure 8) and RT (see Figure 9) in each TOJ tasks (Auditory task: for JND regression weight of age β -0.60, p<0.001, and for RT β -0.69, p<0.001; Visual task: for JND, β -0.47, p<0.001, and for RT β -.66, p<0.001; Tactile task: for JND β -0.72, p<0.001, and for RT β -.80, p<0.001).

3.2.2. Multisensory TOJ Task Analyses

For the multisensory tasks data of thirteen subjects within the age range of 20 to 25 years old were analyzed. Figure 5 shows mean JND (5A), PSS (5B), TBW (5C), and RT (5D) in three multisensory tasks. For the auditory-tactile (AT) task mean JND is 191.31 ± 92.77 ms, for the auditory-visual (AV) task mean JND is 202.62 ± 102.89 ms, and for the visual-tactile (VT) task mean JND is 230.38 ± 95.66 ms (Fig. 5A). For the auditory-tactile (AT) task mean TBW is 268.29 ± 124.34 ms, for the auditory-visual (AV) task mean TBW is 297.20 ± 157.71 ms, and for the visual-tactile (VT) task mean TBW is 325.88 ± 120.59 ms (Fig. 5B). For the auditory-tactile (AT) task mean PSS is 25.13 ± 42.22 ms, for the auditory-visual (AV) task mean PSS 7.42 ± 103.1 is ms, and for the visual-tactile (VT) task mean PSS 53.53 ± 83.16 is ms (Fig. 5C). Mean reaction time (RT) for the auditory-tactile task is 517.77 ± 236.26 ms, for the auditory-visual task 255.45 ± 107.41 ms, and for the visual-tactile task 376.53 ± 232.86 ms (Figure 5D).

3.2.2.1. ANOVA

Separate one-way ANOVAs were conducted with JND, PSS or TBW as the dependent variable and Task (3 levels: AT, VT, AV) as the independent categorical variable. No significant main effect of task was found on any of these three variables (JND: F (2,13) = 0.56, p= 0.58, partial η2= 0.03; TBW: F (2,13) = 0.59, p=0.56, partial η2= 0.03; PSS: F (2,13) = 1.09, p= 0.35, partial η2= 0.06). On the contrary, one way ANOVA with RT as dependent variable and Task as independent variable revealed a main effect of task: F (2,13) = 5.53, $p<0.01$, partial η2= 0.23. Tukey's HSD post-hoc analysis showed the mean difference in RT was significant only for comparison between AV and AT ($p<0.01$).

3.2.2.2. Pearson's Correlation Between Dependent Variables

Pearson's correlation between JNDs or RTs from three multisensory tasks is summarized in Table 2. No significant correlation between JNDs (Table 2A) were found, but reaction times in three tasks - auditory-tactile (rt_at), auditory-visual (rt_av), and visual-tactile (rt_vt) were significantly correlated with each other (ps <0.05) (Table 2B).

3.2.2.3. Multiple Linear Regression

Multiple regressions were conducted to predict JND, PSS, TBW, or RT in the multisensory tasks by age, sensory profile scores, IQ percentile scores of the 12 subjects who had completed sensory profile in addition to TOJ tasks and IQ profile. Regression model was found significant for auditory-tactile PSS (adjusted R^2=0.80, F (7,4) =7.33, $P<0.05$) with low registration (β 0.73, $p<0.05$) and sensory avoiding (β 0.72, $p<0.05$) being the significant predictors of the model. Regression model was marginally significant in predicting the auditory-visual task TBW (adjusted R^2=0.74, F (7,4) =5.56, P=0.06), with low registration (β -0.63, $p<0.05$) and sensory seeking (β 0.98, $p<0.05$) being the significant predictors. Except for these instances, rest of the regression models were found non-significant in AV task (for JND: Adjusted R^2 = 0.415, F(7,4) = 2.15, $p> 0.05$; for PSS: Adjusted R^2 = -0.59, F(7,4) = 0.41 , $p> 0.05$; for RT: Adjusted R^2 = 0.18 , F(7,4) = 1.34 , p> 0.41), in AT task (for JND: Adjusted R^2 = 0.19, F(7,4) = 1.37, p> 0.05; for TBW: Adjusted R2 = 0.21, F(7,4) = 1.42, p> 0.05; for RT: Adjusted R^2 = -0.33, F(7,4) = 0.61, p> 0.05), and in VT task (for JND: Adjusted R^2 = -0.76, F(7,4) = 0.32, p> 0.05; for PSS: Adjusted R2 = 0.25, F(7,4) = 1.52, p> 0.05; for TBW: Adjusted R2 = -0.59, F(7,4) = 0.42, p> 0.05; for RT: Adjusted R^2 = 0.63, F(7,4) = 3.72, p> 0.05). Intelligent Quotients were not significant predictors of any of the matrices.

Follow-up correlation showed significant positive correlation of auditory-tactile PSS with low registration (r(10) =.77, p <.01), and sensory avoiding (r(10) =.62, p <.05). Significant positive correlation was also found between auditory-visual TBW and sensory seeking pattern (r(10) = .62, p <.05), but not between auditory-visual TBW and low registration pattern (p>.05). Bivariate scatterplot between auditory-visual TBW with low registration showed outliers with relatively high TBW and low sensory z-score (Figure 6D). Scatterplot for auditory-tactile PSS with predictors: low-registration and sensory avoiding patterns, and for auditory-visual TBW and sensory seeking pattern are presented in Figure 6 (Figure 6A, 6B, 6C).

3.2.3. Linear regression between independent variables

Linear regression between independent variables- age, IQ percentiles and Sensory quadrant Z-scores (data from 37 subjects) had revealed marginally significant association between age and Full -Scale IQ percentile (β -0.33, p <0.05) (Figure 7A) suggesting Full scale IQ decreases slightly with age within this group of subjects. Full scale IQ percentile also showed significant positive association with performance IQ percentile (β 0.87, p <0.001) (Figure 7B), suggesting both IQ profiles develop simultaneously.

3.2.4. Comparison of Thresholds in Unisensory and Multisensory Tasks

Comparison of JND values had been made between unisensory and multisensory tasks, with data from 13 subjects (20 to 25 years old) who participated in both unisensory and multisensory tasks. Linear regression model was conducted with JND value being the dependent variable and Task modality (2 levels: unisensory vs. multisensory) being the independent variable. JND value for the multisensory tasks were significantly larger than the JND value in the unisensory tasks (F (1,76) = 59.17, $p< 0.001$). To further evaluate this difference between JND in unisensory and multisensory tasks, one way ANOVA was conducted with JND values being the dependent variable and Task modality with six levels (3 unisensory and 3 multisensory) being the independent categorical variable. A significant effect of task on JND was found (F (5,12) =14.62, $p<0.001$). Tukey's Post-hoc analysis indicated that JND values for each multisensory task were significantly higher than those from each unisensory task (between visual-tactile and visual/tactile/auditory: all ps <0.001; between auditory-tactile and visual/tactile/auditory tasks: all ps ≤ 0.05; between auditory-visual and visual/tactile/auditory: all $p < 0.05$). Pearson's Correlation between JND values in unisensory and multisensory tasks were also analyzed. As seen in Table 3, no statistically significant correlation was found between JNDs in both tasks.

Chapter 4

Discussion

Temporal sensitivity in unisensory TOJ tasks improves with age

The findings of this study along with the line of existing literature demonstrate effect of age on temporal sensitivity of perception for neurotypical children and young adults in visual, auditory, and tactile modalities. While previous studies reported age-related increase in thresholds across all major sensory modalities in older adults (Fink, 2005; Szymaszek, 2006; Busey et al., 2010; Ulbritch, 2009; Craig, 2010; Laasonen, 2002), our study showed thresholds in these sensory domains decrease with age, reflecting the development of unisensory temporal processing from childhood to young adulthood. Following the same pattern, reaction time in these tasks also decreases with age. The persistent pattern of improving in the TOJ task performance and speed with increasing age within this group suggests that there is no "trade off" between accuracy and speed.

Performance in visual TOJ task was better

Both threshold and reaction time were the lowest in the visual TOJ task; although, both parameters showed large individual variabilities in all three tasks. Post-hoc analysis suggested that visual threshold was significantly lower than that of auditory task and tactile task, but difference in threshold was not significant between the auditory and tactile tasks. The unisensory TOJ task paradigms of the current study used qualitatively identical stimuli from the same auditory/visual/tactile modality in different spaces; hence it more specifically illustrates successiveness of stimuli presented in two space, as illustrated by an early pioneer study of TOJ (Hirsh, 1961) as "temporal order in space." Findings of this study support the suggestions of visual dominance in judging spatial cues (Howard & Templeton, 1966; Hirsh, 1961; Foss-Feig, 2008), evident by better performance in the visual TOJ task compared to auditory and tactile tasks. However, thresholds for the three unisensory TOJ tasks were significantly correlated to each other, which might suggest a consistent pattern of improvement in the perceptual abilities in this group of subjects. The correlation between JNDs was most significant for auditory and tactile TOJ tasks. Merchel and Altinsoy (2020) suggested that these two modalities show frequency dependent perceptual ability, and at low frequency stimuli, these modalities show significant resemblance in perceptual threshold levels. Our finding of close association between auditory and tactile thresholds also supports the resemblance in precision of auditory and tactile temporal processing.

For the RT, post-hoc analysis revealed significant differences in each pair of tasks. The most significant difference was between the visual and tactile TOJ tasks and between auditory and tactile TOJ tasks. One limitation for evaluating RT is that the tactile task asked subjects to give a response by pressing the corresponding pedal with their foot, which could be difficult particularly for children. Longer RT in tactile TOJ tasks compared to visual or auditory TOJ tasks could have resulted from this fact. Reaction times in three tasks were significantly correlated with each other, suggesting a consistent pattern of improvement in performance in this group of subjects.

Age, cognitive ability, and sensory sensitivity predicting performance in Unisensory TOJ tasks

Multiple regressions were conducted to examine whether the performance in these unisensory TOJ tasks could be predicted by participants' age, IQ profiles and sensory profiles. Participants' age significantly predicted both threshold and reaction time in all three TOJ tasks. Decline in both threshold and reaction time with age was highest for the tactile task and was lowest for the visual task. This might suggest that visual temporal processing evolves more steadily from childhood to adulthood compared to the other two sensory modalities.

IQ percentiles and the sensory profile scores did not predict performance in the unisensory TOJ tasks except for two instances: JND in the visual TOJ task and reaction time in the tactile TOJ task. JND in the visual task was predicted by a low registration sensory score indicating that participants with higher scores in this measurement of sensory profile would have lower JND value and thus better temporal acuity in vision. A higher score in low registration reflects a higher chance of missing sensory cue (Dunn, 2014). Our finding contradicted Poole's claim (2017) that a higher score in this atypical sensation would predict higher JND or lower temporal acuity as it indicates increased difficulty in recognizing sensory information separated in time. However, a follow-up correlation test did not show statistically significant correlation between these two variables, while bivariate scatterplot showed a few outliers (Figure 4A). Hence further evaluation of this association is required with a larger number of subjects.

Response time in the tactile TOJ task was predicted by performance IQ percentile. Subjects with higher performance percentile would have higher response time in tactile TOJ task, which is contradictory to the existing literature suggesting better cognition would result in faster responses (Baratchu et al., 2009; Deary et al., 2001). A follow-up correlation test did not find any significant correlation between reaction time in tactile

TOJ and performance IQ, and a scatterplot showed a few outliers (Figure 4B), which could cause these contradictory results. Further evaluation of this association is needed to confirm the result.

Linear regression among independent variables including age, IQ and sensory responsiveness patterns of the subjects showed a significant positive correlation between full-scale IQ and the performance IQ (Figure 7B). Full-scale IQ also showed a marginally significant decline with age (Figure 7A); although, a scatterplot between these two variables showed a few outliers.

Multisensory TOJ tasks: Task effect only on RT

For multisensory TOJ tasks, we measured JND, PSS, TBW, and RT. Participants who participated in the multisensory TOJ tasks ranged in age from 20 to 25 years, too small for us to examine the effect of age on multisensory TOJ task performance. When different bimodal tasks were compared, we found significant main effect of task on RT, but not on JND, PSS or TBW. Post-hoc analysis showed that RT was only significantly different between auditory-visual and auditory-tactile TOJ tasks. Again, the difficulty to respond with the foot pedal in the tasks involving tactile stimulation (e.g., auditory-tactile) could have contributed to the differences in the RT.

Age, cognitive ability, and sensory sensitivity predicting performance in Multisensory TOJ tasks

Multiple regression analyses were conducted to examine whether the dependent variables in these multisensory TOJ tasks could be predicted by participants' age, IQ profiles and sensory profiles. Since a relatively small group of subjects within a narrow age range (12 subjects, 20-25 years) participated in these tasks, any association of age with the performance was not expected and was not noted. The sensory profile predicted TBW in the auditory-visual TOJ task and PSS in the auditory-tactile task. TBW in the auditory-visual task was predictable by two sensory profile measures: the sensory seeking pattern and the low registration sensory pattern. Participants who had a higher score in the sensory seeking pattern (i.e., actively seeking for sensory inputs more than others) tended to have a wider binding window in auditory-visual TOJ task. The sensory seeking pattern is frequently associated with hypo-responsiveness, commonly noticed in ASD population (Baranek et al., 2006; Ausderau et al., 2014), who also show wider TBW compared to their neurotypically developed peers. Follow-up correlation showed significant positive correlation between these variables (Figure 6C), confirming the predictive role of the sensory seeking pattern.

The low registration sensory pattern was a marginally significant predictor of audio-visual TBW. Participants who had higher scores in this measure (i.e., more likely to miss sensory inputs than usual) tended to have narrower TBW in the auditory-visual TOJ task. However, the follow-up correlation analysis did not show significant correlation between these variables, and a bivariate scatterplot showed a few outliers (Figure 6D).

Auditory-tactile PSS was predicted by the low registration pattern suggesting individuals who report higher scores in the low registration measure would have a bias for the auditory signal (i.e., requiring more tactile leading SOA in the auditory-tactile

TOJ task to perceive synchrony). The auditory-tactile PSS was also predicted by the sensory avoiding pattern, suggesting individuals who tend to avoid sensory inputs more than others would also have a bias towards the auditory stimulus over the tactile stimulus. The follow-up correlations showed significant positive correlations of the auditory-tactile PSS with the low registration, and with the sensory avoiding patterns of the sensory profile. IQ profiles did not predict JND, PSS, TBW or RT in these multisensory tasks.

Previous studies showed relationship between age induced decline in cognition and perceptual ability (Szymaszek, 2009; Nowak, 2016; Ulbritch, 2009) in adult population. These studies suggested a “common cause” theory for shared variance in cognition, sensation, and sensory-motor function deterioration in adult and older subject groups. The current study revealed an age induced improvement in the unisensory temporal processing (precision and reaction time) from childhood to adulthood. Although this study was not able to examine the effect of age on the multisensory TOJ task performance, findings from the unisensory TOJ tasks are consistent with our *hypothesis* that young participants would perform better than the children. In addition, our finding of sensory responsiveness predicting perceptual capability in the multisensory TOJ tasks partially support our second *hypothesis* that perceptual ability of the participants could be predicted by their sensory responsiveness patterns and cognition.

One potential contributor to age induced improvement in temporal processing is the development of myelination. Development of myelination is commonly studied as an estimator of neural maturation (Gibson, 1991). A considerable number of studies concluded that there is a linear increase in the volume of white matter of brain, including myelination until late adolescence (20/22 years) (Giedd et al., 1999; Reiss et al., 1996; JERNIGAN et al., 1991; Giedd et al., 1996). Maturation of myelination patterns is also believed to be extended to adolescence (Chugani et al.,1987), with cortical layers involved with information processing seem to develop slowly than the other layers (Huttenlocher et al., 1997). The development of myelination could potentially facilitate temporal processing, giving rise to the age-related improvement observed in our study. Furthermore, temporal acuity has been shown to be impaired in some conditions that affect myelination. For instance, multiple sclerosis, a condition that is associated with demyelination of white matter in central nervous system, results in deficits in auditory and visual temporal resolution (White et al., 1983; Rappaport et al., 1994).

Thresholds: Unisensory vs multisensory tasks

JNDs in the multisensory tasks did not show significant differences between the tasks. To examine whether there was any difference between unisensory and multisensory temporal thresholds, linear model analysis was conducted (with data from 13 subjects). Participants performed better in the unisensory tasks compared to multisensory tasks, as in all paired comparisons JND in multisensory task was significantly higher than that of unisensory task. Our finding of better performance in the unisensory TOJ tasks compared to the multisensory TOJ tasks supports the hypothesis of a classic literature exploring temporal resolution between different modality signals (Exner, 1875). This early study suggested that sensory signals from the same sense should be better organized in time than the signals from the different sensory modalities would do. According to Hirsh (1961), unisensory TOJ naturally measures the “successiveness” of the temporally separated signals from the same sense, rather than “order” of the signals, which might also result in lower thresholds for the unisensory TOJ tasks than that of the multisensory tasks. However, JND values in the unisensory and multisensory tasks were not significantly correlated with each other, which might be attributed to the small number of participants included in this analysis.

Conclusion

This study, to our best knowledge, is the first study that aimed to assess the temporal processing within and across three modalities (visual, auditory, tactile) in both children and young adult neurotypical participants. This study offered to evaluate the contribution of the participants’ age, cognitive ability, and sensory responsiveness to their temporal processing abilities. It is important to characterize the perceptual resolution in the NT groups that often used as controls in studies with neurologically atypical groups, since the individual variability within the NT group can affect between-groups differences (Poole et al., 2015). While previous studies examining temporal perception mostly focused on neurologically atypical groups (e.g., ASD and ADHD), results from our study provide new insights about natural development in the temporal processing, setting a unique benchmark for the future relevant studies to mark “normal” or “deviation from normal.” Note that our study included a wide range of SOAs, therefore lengthy trials might have resulted in fatigue and deterioration of the attentional span for the participants, contributing to the large variability observed in their performance. Another limitation of this study is that it has a relatively small number of participants, especially for the multisensory TOJ tasks. Future studies with a larger group of participants are needed to confirm our findings.

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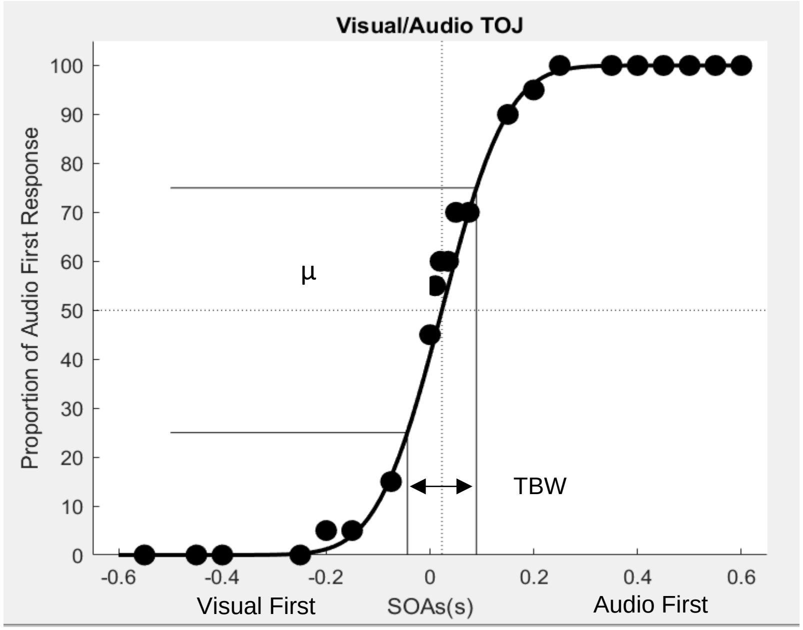
Figure 1

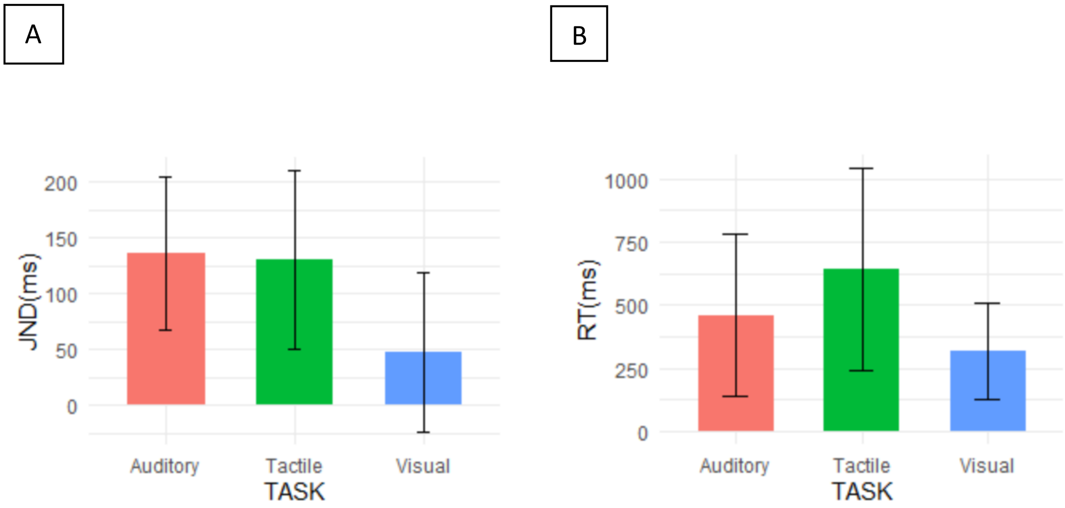
Example Psychometric Function Fitting ***for Audio-visual TOJ task***



The proportion of “Auditory First” response in Audio-visual TOJ task plotted as a function of SOA. Mean of the fitted curve (μ) referred to the Point of Subjective Simultaneity (PSS); Slope of the distribution gives the standard deviation of distribution and represents Just Noticeable Difference (JND). Temporal binding Window (TBW) represents sum of the absolute values of threshold for 25% and threshold for 75% “Audio First” response.

Figure 2

MEAN JND and RT in Unisensory TOJ Tasks



A. Mean JND value with standard error in Auditory, Tactile, and Visual TOJ tasks. B. Mean RT in Auditory, Tactile, and Visual Tasks.

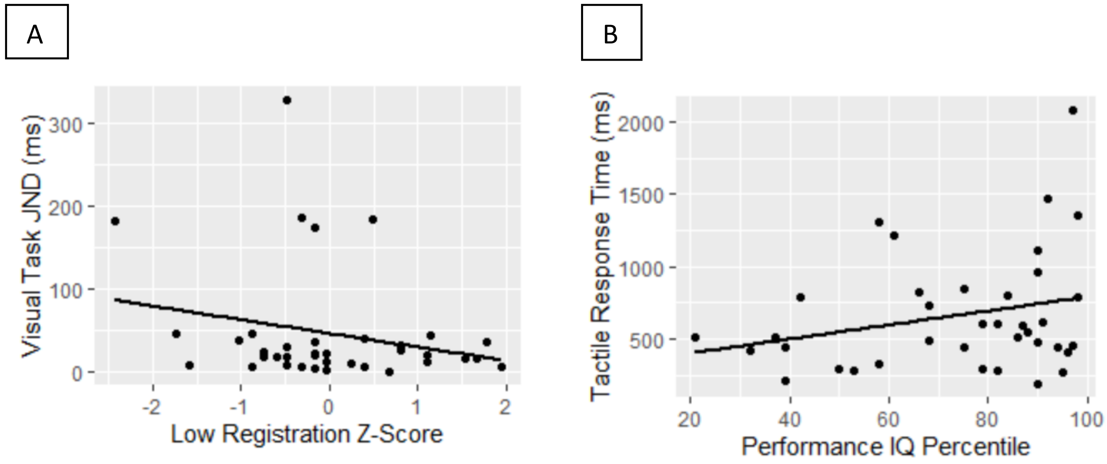
Figure 3

Regression Line of JND with Age in each Unisensory TOJ Task

Best fitted regression line for JND with age in each unisensory TOJ task: Auditory task (red), Tactile task (green), and Visual task (blue).

Figure 4

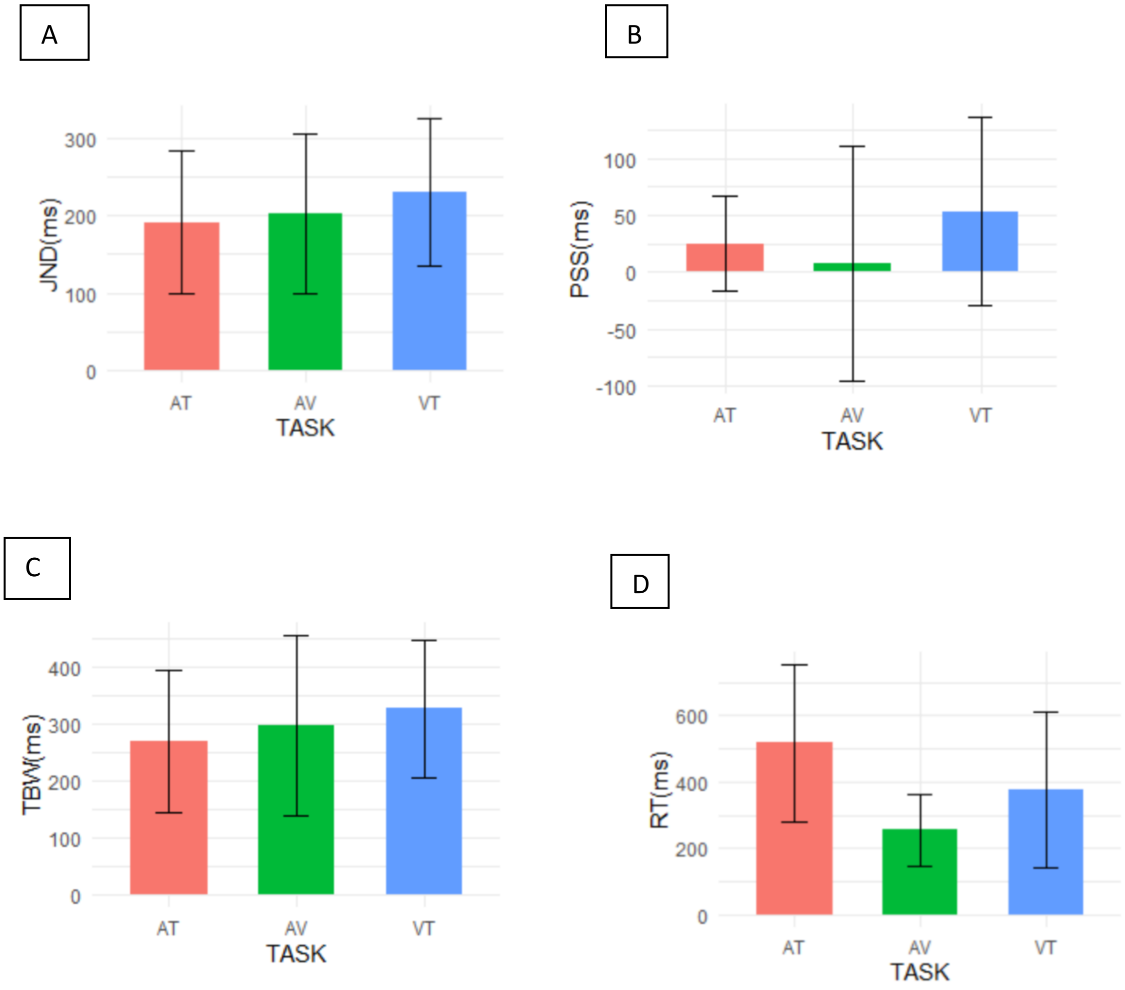
Associations Between Perceptual Measures of Unisensory Tasks and Cognitive/Sensory Measures



Association between JND in visual TOJ task and low registration pattern of sensory responsiveness (A); between response time in tactile TOJ task and performance IQ percentile (B).

Figure 5

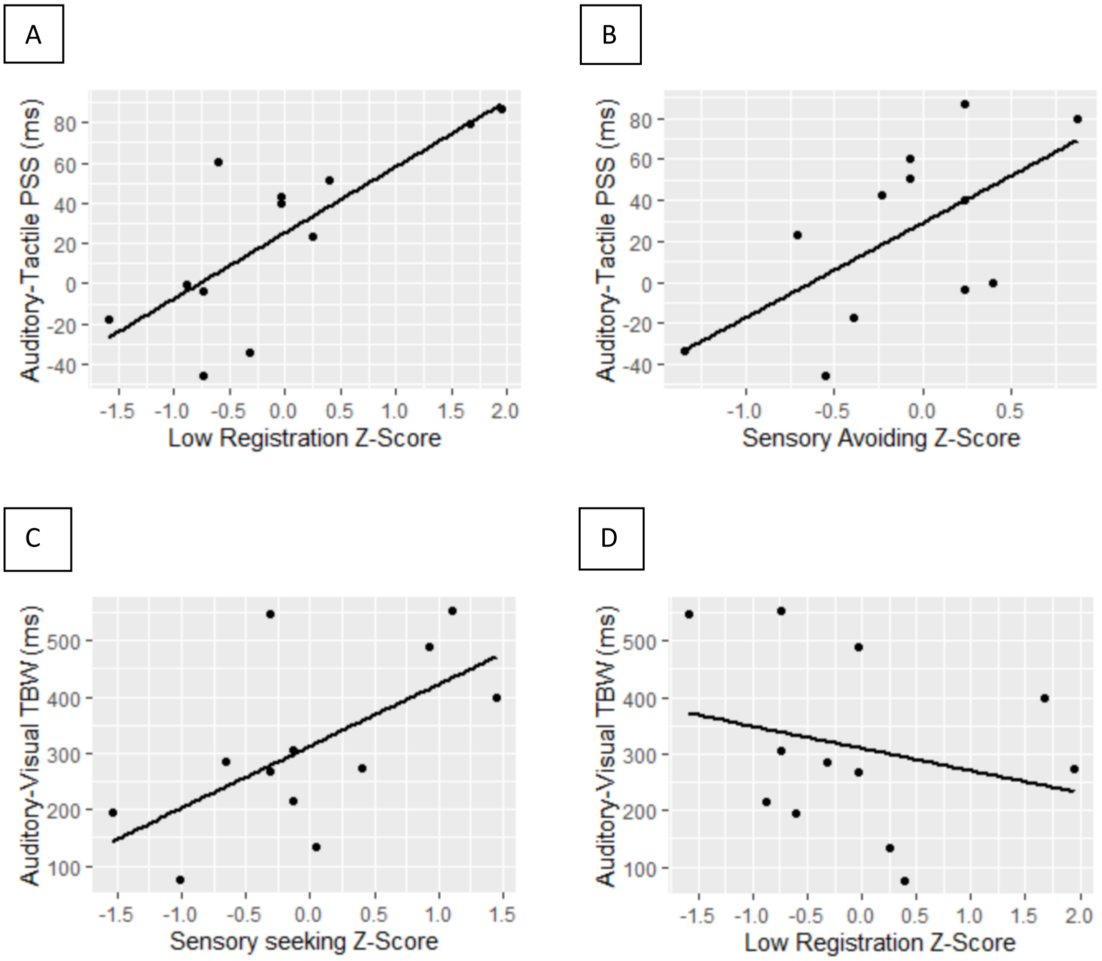
MEAN JND (A), PSS (B), TBW (C), and RT (D) in Multisensory Tasks



A. Mean JND; B. Mean PSS; C. Mean TBW, and D. Mean RT with standard errors in auditory- tactile (AT), auditory-visual (AV) and visual-tactile (VT) TOJ tasks.

Figure 6

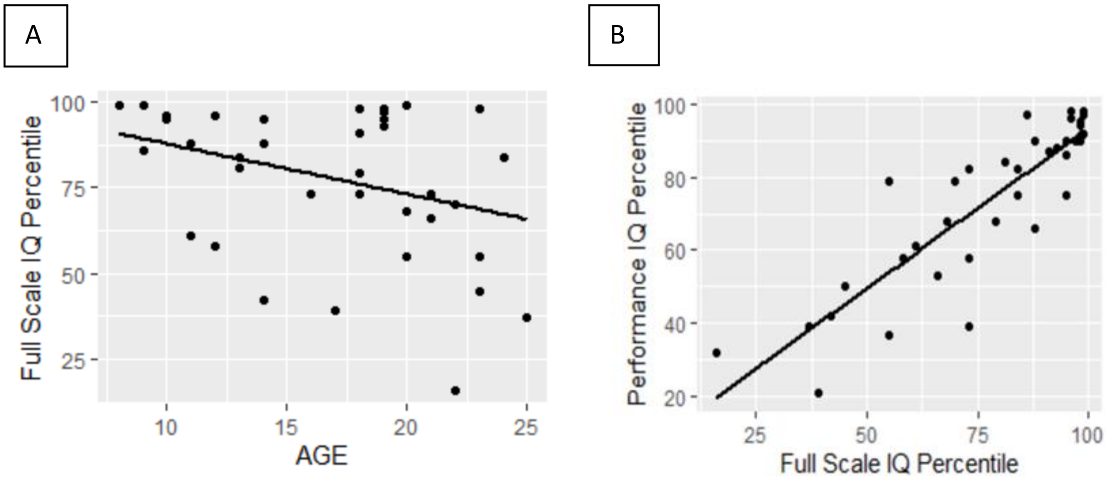
Associations Between Metrices of Multisensory tasks and Sensory Profile Patterns



Association between matrices of multisensory integration and patterns of sensory responsiveness: between Auditory-Tactile PSS and Low Registration Z-scores (A), Sensory Avoiding Z-scores (B); between Auditory-Visual temporal binding window (TBW) and Sensory Seeking Z-scores (C), low registration Z-scores (D).

Figure 7

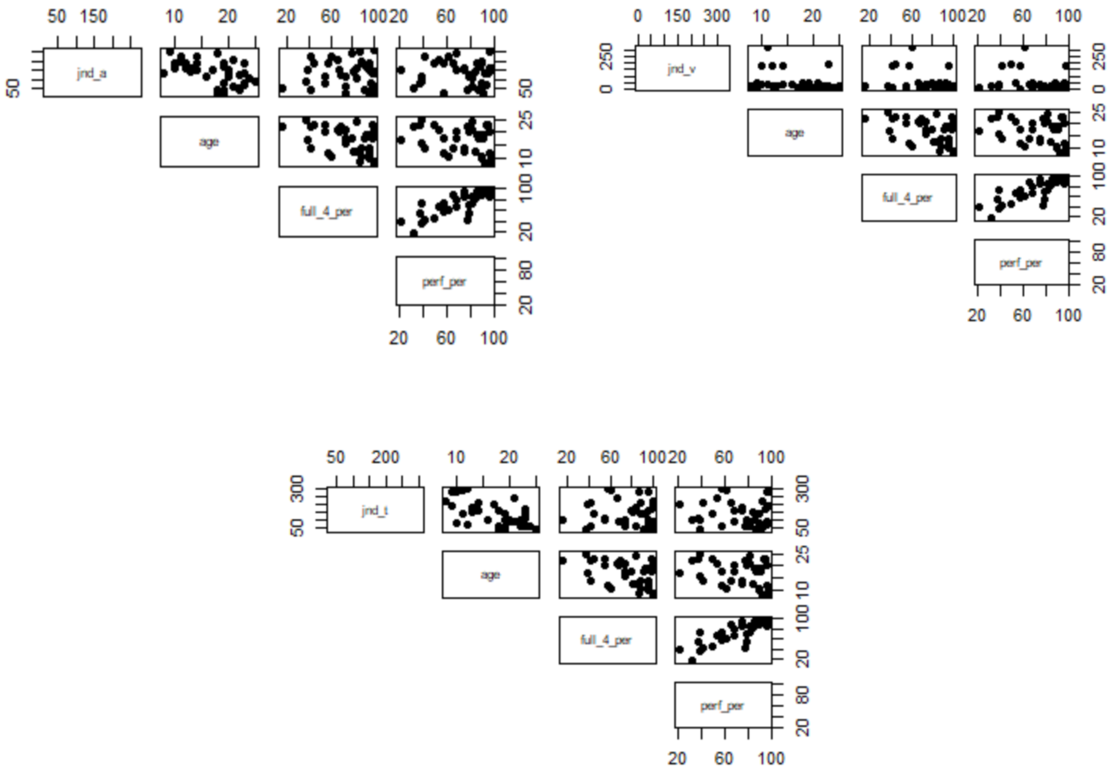
Associations Between Independent Variables



Association between Full scale IQ percentile and AGE (A); between Performance IQ percentile and Full scale IQ percentile (B).

Figure 8

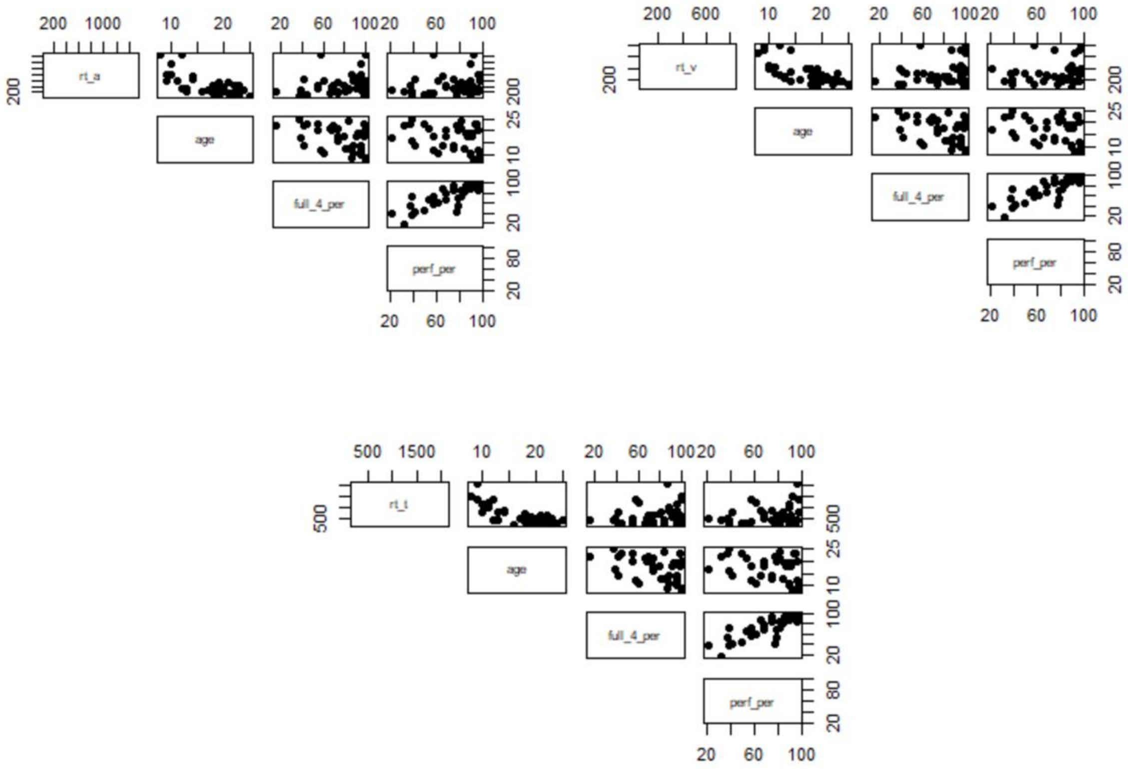
Scatterplot Matrix for Multiple Regression Models Predicting JND Values in Unisensory TOJ Tasks



Scatterplot matrix predicting JND values based on age, performance IQ percentile (perf_per), and Full-scale IQ percentile (fill_4_per). A. JND in auditory TOJ task (jnd_a); B. JND in visual TOJ task (jnd_v); C. JND in tactile TOJ task (jnd_t).

Figure 9

Scatterplot Matrix for Multiple Regression Models Predicting RT Values in Unisensory TOJ Tasks



Scatterplot matrix predicting RT values based on age, performance IQ percentile (perf_per) and full-scale IQ percentile (fill_4_per). A. RT in auditory TOJ task (rt_a); B. RT in visual TOJ task (rt_v); and C. RT in tactile TOJ task (rt_t).

Table 1

Pearson's correlation matrix between dependent variables(A) JND, (B) RT of unisensory tasks. Correlation coefficients with adjusted p ≤0.05 are bolded to highlight significant association between variables.

A

	jnd_a	**jnd_v**	**jnd_t**
jnd_a	1	**0.4**	**0.68**
jnd_v		1	**0.65**
jnd_t			1

Note. jnd_a, jnd_v, and jnd_t represents JND in auditory, visual, and tactile TOJ task, respectively.

B

	rt_a	**rt_v**	**rt_t**
rt_a	1	**0.73**	**0.76**
rt_v		1	**0.79**
rt_t			1

Note. rt_a, rt_v, and rt_t represents response time in auditory, visual, and tactile TOJ task, respectively.

Table 2

Pearson's correlation matrix between dependent variables (A) JND (B) RT of Multisensory tasks. Correlation coefficients with adjusted p ≤0.05 are bolded to highlight significant association between variables.

A

	jnd_at	**jnd_vt**	**jnd_av**
jnd_at	1	0.47	0.38
jnd_vt		1	0.44
jnd_av			1

Note. jnd_at, jnd_vt, and jnd_av represent JND in auditory-tactile, visual-tactile, and auditory-visual TOJ task, respectively.

B

	rt_at	**rt_vt**	**rt_av**
rt_at	1	**0.76**	**0.76**
rt_vt		1	**0.76**
rt_av			1

Note. rt_at, rt_vt, and rt_av represent response time in auditory-tactile, visual-tactile, and auditory-visual TOJ task, respectively.

Table 3

Pearson's correlation matrix between JND values in Multisensory and Unisensory Tasks

	jnd_a	**jnd_v**	**jnd_t**	**jnd_at**	**jnd_vt**	**jnd_av**
jnd_a	1	0.56	0.5	0.08	0.07	-0.28
jnd_v		1	0.41	0.21	0.21	0.06
jnd_t			1	0.52	0.7	0.33
jnd_at				1	0.47	0.38
jnd_vt					1	0.44
jnd_av						1

Note. jnd_a, jnd_v, jnd_t, jnd_at, jnd_vt, and jnd_av represent JND values in auditory, visual, tactile, auditory-tactile, visual-tactile, and auditory-visual TOJ tasks, respectively.