

Assessing Changes in Visual Attention Secondary to Mild Hearing Loss in Aging
through the Study of Response Time and Event-Related Potentials

by

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Abstract

This set of studies was designed to evaluate the association between hearing loss in aging and extra-auditory cognitive decline by assessing younger normal-hearing adults (YN), and older adults with either age-typical hearing (ONHA) or mild hearing loss (OHL). A visual reaction time (RT) paradigm involving four tasks with hierarchically-varied attentional demands was administered with EEG. There were three main objectives. The first objective (Study 1) was to assess the effect of hearing loss on: i) RT, ii) error commission and recovery, and iii) strategic versus automatic response preparation. The OHL group demonstrated general slowing on the simplest tasks, less efficient error recovery, and difficulties with automatic response preparation, compared to both other groups. The second objective (Study 2) was to study the YN group's EEG results using the N1 to identify the influence of task context on early attention-sensory evaluation and the scalp distribution of the P3 as a marker of attention guiding (anterior) and stimulus categorization and response preparation (posterior). The latency and amplitude of the N1, the posterior-anterior P3 amplitude distribution, and neural activity modeling supported an increasing reliance on anterior attentional processes as tasks required either an enhancement or suppression of attention for stimulus discrimination. The third objective (Study 3) was to compare the EEG data between the ONHA and OHL groups using the metrics used in Study 2.

The OHL group had a longer N1 latency that correlated with their speeded visual executive test scores, longer anterior P3 latencies, hemispheric symmetry of N1 amplitudes indicative of less efficient top-down control, and anterior P3 amplitudes that indexed over-processing of unnecessary information. Latency and amplitude of the posterior P3 were comparable between both older groups. In sum, cognitively-intact older adults with mild hearing loss demonstrated differences in: i) response time on the simplest tasks and automatic preparatory processes compared to younger adults and older adults with age-typical hearing; and ii) ERP indices of sensory-cognition integration and early attentional guiding compared to older adults with age-typical hearing. These findings may represent mechanisms involving either localized differences in subcortical regions of sensory-motor-cognitive integration and/or disruptions of functional networks.

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Chapter 1

Background and Rationale

1 Background and rationale

1.1 An introduction to the relationship between hearing loss in aging and cognitive decline

A common complaint that occurs with aging is that of a reduction in hearing ability (presbycusis), especially in the context of tracking and contributing to conversation (CHABA, 1988). This complaint deepens as the situational complexity increases, as, for example, when the target auditory signal is degraded (Heinrich, Schneider, & Craik, 2008; Pichora-Fuller, Schneider, & Daneman, 1995; Wingfield, Tun, & McCoy, 2005) or when there is competing environmental noise (Gordon-Slant & Fitzgibbons, 1995; Tun, O’Kane, & Wingfield, 2002). Decades of epidemiological, laboratory, and clinical studies have provided mounting evidence of an important association between hearing loss and cognitive decline in older adults (e.g., Albers et al., 2015; Baltes & Lindenberger, 1997; Humes, Busey, Craig, & Kewley-Port, 2013; Humes & Levi, 2016; Li & Lindenberger, 2002; Lindenberger & Baltes, 1994; Lindenberger & Ghisletta, 2009). The need to understand the mechanisms underlying the association between auditory and cognitive decline is driving ongoing research, especially given the potential for shaping clinical practice and health promotion policy with respect to maintaining cognitive health and delaying dementia in older age (for reviews see Livingston et al., 2017; Martini, Castiglione, Bovo, Vallesi, & Gabelli, 2014). However, it is difficult to develop a single model/theory of possible mechanisms underlying this association due to the complicated relationship between age-related changes in sensory/perceptual (e.g., audibility, auditory temporal processing), cognitive (e.g., effortful attending and working memory), and socio-emotional (e.g., social isolation) factors (Albers et al., 2015; Baltes & Lindenberger, 1997; Lin et al., 2013; Tun, Williams, Small, & Hafter, 2012; Pichora-Fuller et al., 2016; Pichora-Fuller, Alain, & Schneider, 2017).

Normal aging is associated with changes in the outer, middle, and inner ear, but only changes to the inner ear are known to consistently and significantly lead to deficits in auditory processing (Chisolm, Willot, & Lister, 2003; Schneider, 1997). The median pure-tone audiometric thresholds for older adults who are 60 to 80 years of age are within what are considered to be clinically normal limits if they are < 25 dB HL for frequencies below 4 kHz

(ISO, 2017). Outer hair cell loss due to noise exposure can cause high-frequency hearing loss at any age. High-frequency hearing loss can also be caused by reductions in the endo-cochlear potential due to age-related changes in the blood supply to the cochlea in the stria vascularis. Pure-tone threshold testing is one of the most common ways to assess age-related hearing loss and the audibility of speech sounds can be estimated using these thresholds (Chisolm et al., 2003; Schuknecht & Gacek, 1993). Yet pure-tone sensitivity does not consistently or reliably predict real-life auditory performance on tasks such as understanding speech in noise (Gordon-Salant, 2005; Houtgast & Festen, 2008). As examples, age- and noise-related damage may occur within synapses between inner hair cells and the cochlear neurons leading to the brain (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017) and such synaptopathy may not be detected using standard pure-tone assessments (Pienkowski, 2017; Tremblay & Backer, 2016). Such a problem at the synaptic level may lead to difficulty within the central auditory system during the encoding of temporal characteristics of sound that are essential to speech understanding (Kujawa & Liberman, 2009; Liberman & Kujawa, 2017). Moreover, listening also often engages cognitive processes such as attention and memory which could place exceptional burden upon the central aspects of the auditory system, especially in adverse listening situations (Peelle, 2018). Therefore, age-related changes that occur in centralized neural functioning are hypothesized to contribute to the dysfunctional supra-threshold auditory processing experienced by many older individuals in everyday life (Benichov et al., 2011). Thus, there can be both threshold and supra-threshold auditory declines with age.

Clinical observations and research studies that have examined the relative contributions of sensory-based versus brain-based factors contributing to the hearing loss/cognition association have produced variable results. Clinically, there are many people with an audiometrically-measured hearing impairment who appear little affected on most daily tasks. This could be related to several factors, such as adapting our lives to meet our functional abilities as we age (Phillips, 2016), or having the cognitive capacity to compensate for reduced sensory information (Pichora-Fuller & Singh, 2006; Pichora-Fuller, 2008). Additionally, a sensory-cognition association can be affected by factors such as individual personality, motivation, self-efficacy, social support versus isolation, and conation (the purposeful effort required to complete a task that is distinct from individual motivation) (Mackersie & Calderon-Moultrie, 2016; Matthen, 2016; Phillips, 2016; Pichora-Fuller, 2016; Pichora-Fuller et al., 2016). Early studies that largely

focused on speech understanding found that audiometric loss accounted for most of the variability in task performance over other cognitive factors (Humes, 1996; van Rooij & Plomp, 1992). However, those studies tended to use simplistic language stimuli that did not necessarily tap higher cognitive processes that could influence speech understanding. Later studies supported a hypothesis of the contributions of auditory temporal processing and cognition to speech understanding after controlling for audibility (Helfer & Freyman, 2008; Humes, 2007). Assessing age-related hearing loss then would benefit from finding appropriate metrics that can capture the full scope of central cognitive processes. Likely the processes are especially sensitive to aging including attention, processing speed, working memory, executive function, and the inhibition of distracting information (Baddeley, 2002; Hasher & Zacks, 1988; Logie, 2011; McDowd & Shaw, 2000; Miyake et al., 2000; Salthouse, 1994a,b, 1996; Tun & Lachman, 2010; Verhaeghen & Cerella, 2002; West, 1996).

1.2 The specific versus general nature of the association between hearing loss in aging and cognition

1.2.1 Hearing loss and auditory-based cognition

Given the critical role that cognitive functions such as processing speed, attention, working memory, and executive function play in speech processing, it was previously hypothesized that age-related declines in these aspects of cognition would interact with age-related declines in auditory processing (Benichov et al., 2011; Cohen, 1987; Wingfield & Lash, 2016). Evidence from neuroimaging studies shows age-related differences in activation underlying the cognitive processes that are important for speech processing such as dividing and switching attention and inhibiting distraction (DiGirolamo et al., 2001), and also hearing-related differences in brain activation associated with these processes (Pelle, Troiani, Wingfield, & Grossman, 2010). Converging evidence from behavioural studies suggests that processing speed may play an especially important role in speech understanding (Tun, 1998; Tun, Wingfield, Rosen, & Blanchard, 1998). For instance, older adults with slower processing speeds experience more difficulty than both older adults with relatively faster processing speeds and younger adults during the comprehension of speech when it is presented rapidly (Gordon-Salant & Fitzgibbons, 1995; Wingfield, McCoy, Pelle, Tun, & Cox, 2006; Wingfield, Tun, & Rosen, 1995). Grassi

and Borella (2013) found that certain auditory abilities were able to explain a small amount of variance in processing speed scores amongst older adults but not working memory or inhibition scores. Those auditory abilities included the ability to discriminate sounds by frequency, duration, long-term spectrum, and envelope. Other auditory abilities such as 1-kHz absolute threshold, the ability to discriminate between the intensities of tones, and gap detection did not explain any of the variance in cognitive performance, including processing speed. Grassi and Borella suggested that processing speed is a lower-level cognitive ability that underlies other abilities such as working memory and inhibition (see also Salthouse & Babcock, 1991), and that the auditory abilities that may help explain differences in processing speed are associated with the time needed for central/computational operations. The processing speed task used by Grassi and Borella was a visual task of the time it takes to compare multiple sets of two strings of letters to assess whether or not each pair were identical. However, in terms of speech understanding, although it is known that there are most likely independent processes occurring at the threshold compared to supra-threshold levels of auditory abilities that contribute to presbycusis (for example see Profant et al., 2019), there is still much to learn in terms of understanding how the different aspects of auditory processing interact with age and cognitive abilities such as processing speed, working memory, and a reduction of inhibitory mechanisms (Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2012; Füllgrabe, Moore, & Stone, 2015; Schattelman, Hughes, & Caspary, 2008; Wingfield, 1996).

The complexity of the language used also contributes to speech understanding. For example, the more syntactically complex a sentence becomes, the more difficult it is to understand, especially so for older adults (Feier & Gerstman, 1980; Kemper, 1986). It has been shown that older adults with hearing impairment have difficulty comprehending syntactically complex speech as reflected in their response latencies and accuracy (DeCaro, Peelle, Grossman, & Wingfield, 2016; Tun, Benichov, & Wingfield, 2010), and that this difficulty with understanding syntactically complex speech can be further exacerbated by the rate of speech presentation (Wingfield et al., 2006). Speech understanding is also influenced by prior experience that contributes to expectancies of what will be said next. An increase in sentence complexity is expected to add cognitive challenge, especially when experience-based expectations are violated (Fodor & Frazier, 1980; Frazier & Fodor, 1978; Gibson, Bergen, & Piantadosi, 2013; Levy, 2008; Marslen-Wilson & Tyler, 1980). Additionally, older adults,

compared to younger adults, have more frequent false hearing (mistaken high confidence in the accuracy of the perception of a spoken word that was actually misperceived) due to a greater reliance on context to aid speech comprehension (Rogers, Jacoby, & Sommers, 2012). This reliance on context does not seem to represent a greater efficiency in the utilization of context and may be related to changes in frontal lobe functioning in aging (reviewed in Rogers et al., 2012).

In the context of common complaints from older adults with hearing impairments, listening effort (Lemke & Besser, 2016; Pichora-Fuller et al., 2016) and the resulting fatigue (see Hornsby, Naylor, & Bess, 2016 for a review of the multifaceted nature of fatigue in hearing loss) have also been recognized as important factors in speech comprehension. As we begin to better understand how auditory perceptual difficulties (Gordon-Salant & Fitzgibbons, 1995; Heinrich et al., 2008; Pichora-Fuller et al., 1995; Wingfield et al., 2005; see Eckert, Teubner-Rhodes, & Vaden, 2016 for a review of listening effort in noise) and higher-order cognitive processes (Larsby, Hallgren, Lyxell, & Arlinger, 2005; Phillips, 2016; Rudner, 2016; Tun et al., 2002; Tun & Wingfield, 1999) utilize more cognitive resources in the context of hearing loss, models and theories can be developed to account for age-related declines in speech comprehension.

1.2.2 Hearing loss and vision-based cognition

The negative interaction between the qualities of stimulus information and cognition (recall and comprehension) is known to apply to other sensory modalities such as vision (Dickinson & Rabbitt, 1991; Gao, Levinthal, & Stine-Morrow, 2012). Likewise, in the collection of literature examining auditory-cognition associations, predictions of a more generalized (i.e., not specific to hearing) connection between sensory and cognitive decline arose from early clinical observations in dementia and from correlational research (Albers et al., 2015; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Uhlmann, Larson, Rees, Koepsell, & Duckert, 1989). Although the definition of dementia focuses on the end-stage connection between changes in cognition and daily functional activities, changes in motor and multiple sensory systems (e.g., audition, vision, touch) can sometimes be observed many years before a measurable decline in cognition and then function (reviewed in Albers et al., 2015). A major issue with clinical observations, however, is that there is yet no consistent pattern or timeline to the presentation of these symptoms that can be connected to the subsequent development of

dementia (Humes et al., 2013; although clinical and cellular models are proposed for dementia relating to Alzheimer's disease in Albers et al., 2015).

In more formal empirical study of multiple sensory system involvement in the relationship between sensory and cognitive decline, the assessment of visual-based cognition is often employed due to our extensive knowledge of the visual system and available tests. However, results of these studies have been mixed. Some studies have shown a decline in visual-based cognition in association with hearing loss. Dupuis and colleagues (2015) showed that, compared to adults with normal sensory functioning, adults with measurable sensory loss (hearing, vision, or both) were more likely to fail the Montreal Cognitive Assessment screening test (MoCA; Nasreddine et al., 2005) even with scoring adjustments to account for sensory decline. This suggested that sensory loss may be associated with greater cognitive loss, even as measured on a screening test. In a longitudinal study, Lin and colleagues (2013) assessed older adults on short measures of global cognitive functioning (the Modified Mini-Mental State test, 3MS; Teng & Chui, 1987) and processing speed using visual stimuli (Digit Symbol Substitution test) over a six-year period. The performance of the older adults with hearing loss worsened faster compared to those with better hearing. These results led to a prediction that older adults with hearing loss would demonstrate a change in performance on the global screening test that is commonly accepted to indicate cognitive impairment (i.e., a 5-point decline) approximately three years faster than older adults with normal hearing. This relationship between hearing loss and cognitive decline was independent of potential confounders such as age or cardiovascular risk factors. An early structural equation model of a large sample of hearing aid users without dementia showed that hearing loss was selectively and negatively correlated with verbal long-term memory performance over and above any influence of visual acuity (Rönnberg et al., 2011). However, a subsequent study showed that hearing loss in non-hearing aid users was also related to performance on short-term and long-term visual memory tests, although the association was stronger for long-term memory than for short-term memory (Rönnberg, Hygge, Keidser, & Rudner, 2014). In a retrospective study, Guerreiro and Van Gerven (2017) showed that declines in performance that were once thought to be prototypical of normal cognitive aging were instead somewhat influenced by hearing ability. Older adults categorized as having 'poor' (compared to those with 'good') hearing showed worse performance on both auditory and visual n-back (working memory) tasks and a Stroop task (inhibitory control).

In contrast to the findings of a decline in vision-based cognition with a decline in hearing, there is evidence that visual processing may be associated with compensation for impoverished auditory processing and/or the maintenance of cognition in aging with hearing loss. Campbell and Sharma (2014) assessed middle-aged adults with either no or early-stage hearing loss. They presented participants with high contrast visual sinusoidal concentric gratings that morphed into a radially-modulated grating or circle-star pattern. Participants with mild-to-moderate hearing loss showed increased visual P1, N1, and P2 amplitudes and decreased N1 latency. Campbell and Sharma proposed that the visual evoked responses may index more efficient visual processing in individuals who have hearing loss, which would compensate for impaired hearing. In older adults, an early behavioural study suggested that people may rely to a greater extent on visible speech cues for comprehending and remembering visual-spoken language as would be experienced during face-to-face conversation (Thompson, 1995). In a more recent study, the correlation between visual acuity and tests of verbal-based cognition (speed, working memory, reasoning, concept formation, and semantic fluency) was statistically significant in older adults with moderate hearing loss but not in older adults with hearing abilities ranging from normal to mild hearing loss (Wettstein, Wahl, & Heyl, 2018). The findings from the Wettstein et al. study suggest that performance on the verbal-based tests was maintained when visual abilities were also maintained in older adults with moderate hearing loss, over and above other factors such as age, sex, education, and a subjective rating of health.

More research is required to address the variability in the existent literature that examines the association between hearing loss and vision-based cognition. For example, in previous studies in which an association between cognitive decline and hearing loss was found, many of the visual tasks used to measure cognition were demanding, requiring high levels of cognitive control, manipulation of information within working memory, and sometimes the assessment of long-term memory processes. There is some evidence in hearing/language-based research that hearing-related differences in performance amongst older adults are elicited by increasing the complexity of stimuli/task (DeCaro et al., 2016). However, this requires further study to assess if older adults with hearing loss are showing an actual generalized decline in the total functioning of multiple sensory domains or just generalized difficulty with complex processing (e.g., due to, for example, the utilization of cognitive resources to compensate for sensory loss instead of their

intended cognitive processing, Pichora-Fuller et al., 1995, while more basic functioning within each sensory system may be intact).

More research is also required to address the contrasting issue of the potential role of visual processing in maintaining cognition or even acting in a compensatory manner in adults with age-related hearing loss, especially by extending studies to include participants at the older end of the age spectrum. Further still, Campbell and Sharma (2014) found evidence of possible compensatory activity by way of increased frontal activity in connection with the measurement of cortical auditory evoked potentials during listening tasks in the middle-aged adults with mild hearing loss. This finding is in line with previous research in older adults with cochlear implants who show increases in frontal activity compared to normal-hearing adults when performing a listening-based task (Henkin, Yaar-Soffer, Steinberg, & Muchnik, 2014; Finke, Sandmann, Kopp, Lenarz, & Buchner, 2015). An increase in frontal activity during cognitive processing has been shown to occur in aging. For example, older adults recruited frontal regions during the performance of one of two tasks and also when switching between the same tasks, whereas younger adults only recruited the same frontal regions when performing the switching function (DiGirolamo et al., 2001). In comparison to low-performing (as measured on standardized memory tests) older adults who recruited similar right frontal regions during a source memory task as young adults, high-performing older adults recruited bilateral frontal regions (Cabeza, Anderson, Loncantore, & McIntosh, 2002). This suggests that high-performing adults were possibly compensating for age-related neural decline (Cabeza, Anderson, Loncantore, & McIntosh, 2002).

1.3 Identified gaps in research on hearing loss in aging and the principles of study design

Gaps. The series of studies presented here were designed to address identified gaps in knowledge concerning cognitive aging and age-related hearing loss. Specifically,

- i) There is a need to further address the issue of sensory modality specificity by using non-auditory tasks, especially given the observed extra recruitment of non-auditory processing in older adults when presented with auditory stimuli (Ouda, Profant, & Syka, 2015) and the variability that exists in the current literature on vision-based cognition in hearing loss.

- ii) There is a need to use simpler, attention-based cognitive tasks that may tap multiple basic processes underlying the cognitive abilities elicited by the complicated, working memory-based auditory tasks that have been used in many studies (Grassi & Borella, 2013).
- iii) There is a need to assess possible connections between sensory loss and shifts in cognitive processing in older adults in the absence of an already-present clinically significant neurodegenerative state (Phillips, 2016). This will help in the identification of possible mechanisms associating hearing loss with cognitive decline when the individual is in a state where this association can be more effectively detected (i.e., before disease has made it difficult to detect this association).
- iv) There is a need to evaluate if the variability in the results from studies assessing vision-based cognition in hearing loss stems from the possibility that some aspects of visual processing may be acting in a compensatory manner.

Principles of Study Design. The studies were designed upon the following principles:

- i) Use visual attention tasks that have already been validated in the clinical literature and that can capture changes in separable attentional processes as task demands change (Feature Integration Task, FIT; Stuss et al., 1989a; Stuss, Stethem, Picton, Leech, & Pelchat, 1989b; Stuss, Binns, Murphy, & Alexander, 2002).
- ii) Use validated outcome metrics that quantify the magnitude and timing of attentional processes (behavioural analysis of RT and analysis of electrophysiological components, EEG); more specifically use metrics that could characterize the attentional processes at early stages of visual processing and relatively later stages of attentional processing involving frontal lobe contributions to assess for activity that may be representative of either a decline in functioning or compensatory activity as suggested from previous research.
- iii) Assess older adults with mild hearing loss, in comparison to young and older adults with age-normal hearing, who were cognitively healthy according to standard measurements.

1.4 The identification of separable processes of attention and their response to healthy aging

The continued refinement of methods for measuring attention has revealed many intertwined (but not necessarily sequential) stages of attentional processing that grossly represent: i) the initial reception and perception of incoming information, ii) localizing attention in space, iii) identifying/recognizing the attended information, and iv) some final form of executive control (e.g., conflict resolution or attention allocation), with or without the requirement of a motor response (Mazza & Brignani, 2016; Posner & Peterson, 1990; Sperduti, Makowski, & Piolino, 2016; Stuss & Alexander, 2007; Williams et al., 2016). These processes recruit a wide range of cortical brain regions, primarily including the dorsal parietal and ventral temporal pathways, the superior parietal cortex, frontal eye fields, anterior cingulate, and prefrontal cortex.

Many studies have examined the effects of aging on the separate attentional processes with variable results. Westlye, Grydeland, Walhovd, and Fjell (2011) examined correlations between performance on measures of the attentional components (alerting, orientation, and executive control) elicited by the often-studied Attention Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) and cortical thickness within the brain networks recruited by each respective component. They found that the relationship between function and anatomy remained stable across a cross-sectional sample of adults ranging from 20 – 84 years of age. This suggests that most individual differences in the structures underlying attention are related to the initial neurodevelopment of brain regions rather than their subsequent neurodegeneration in healthy aging. However, behavioural age-related differences in attention performance are commonly observed, and other research suggests that it may be that not all attentional processes are sensitive to aging in equal measure. Various studies have highlighted the susceptibility of independent networks (alerting; Jennings, Dagenbach, Engle, & Funke, 2007, versus executive control; Zhou, Fan, Lee, Wang, & Wang, 2011) compared to all three networks (Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2010) of attentional processing to the effects of aging. Williams et al. (2016) added electrophysiological measurement during the administration of the ANT to groups of younger and older healthy adults to address the variability found in behavioural findings. Williams et al. found that ERP modulations thought to reflect the early

orienting and alerting processes did not significantly differ between younger and older adults. They hypothesized that many of the previous behavioural findings that showed a decrease in alerting were actually related to speed/accuracy trade-offs, suggesting that older adults use different strategies to complete the task that are difficult to precisely measure using only behavioural variables. Williams et al. found that age-related differences were limited to executive processing. Similarly, in a review of electroencephalographic recordings taken during the administration of different tasks that required people to attend to multiple objects, Mazza & Brignani (2016) concluded that various EEG components that represent different stages of attentional processing are not all affected the same in aging (e.g., all hyper- or hypo-reactive). This occurs possibly as a consequence of factors such as the association of attentional processes with different neural regions that are either relatively more or less sensitive to aging and/or the brain's ability to employ compensatory mechanisms that prevent a change in one attentional process from cascading to other processes (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008; Mazza & Brignani, 2016).

It has been argued that a reaction time collected at the moment of the response represents the sum of the timing of the stages involved for that particular response to have occurred (Sternberg, 1969). This hypothesis presupposes that with additional complexity added to subsequent tasks, the additional required time for response represents the extra time taken for the extra cognitive processes required to deal with the added complexity (Sternberg, 1969; Stuss et al., 2002). Under this assumption, Stuss and colleagues (Hetherington, Stuss, & Finlayson, 1996; Stuss et al., 1989a,b; 2002) developed a series of visual reaction time tasks, known together as the Feature Integration Task (FIT). This series of tasks hierarchically change in complexity both across and within tasks to assess the separable processes of attention within one paradigm. In addition to the sequential introduction of changing task demands, a key component of the task design that differs from most other tasks is the integration of features reflecting changing demands into a single stimulus that remains in a central location. This allows for reassurance that any extra processing introduced with each sequential task was attributed to the processing of just that task-relevant stimulus, and not to extra activities such as scanning a larger search space. This may be especially important since, although we do not yet know for sure that visual attention would respond in the same way as auditory attention, removing spatial ambiguity by presenting

sounds from a single location rather than multiple locations can negate differences in performance (Murphy, Daneman, & Schneider, 2006).

The first task of the FIT, Simple RT, measures baseline response times to the occurrence of every stimulus (the same white-outlined shape). This is followed by three binary choice tasks, administered in a sequential order, with response time measurements to both target and relatively more frequent non-target stimuli. The first binary choice task, Easy Choice RT, assesses the differentiation of stimuli based upon a single feature, the target defined as one white-outlined shape and the non-target stimuli defined as three different white-outlined shapes. The second binary choice task, Complex Choice RT, assesses the differentiation of stimuli based upon the combination of three features (shape, colour, and orientation of line filling) within a single stimulus; the target stimulus is defined by one set of three features and three different types of non-target stimuli share either zero, one, or two features with the target. The third binary choice task, Redundant Choice RT, assesses focused attention and the ability to ignore irrelevant information. The stimuli were defined by three features as in the Complex Choice task but none of the non-target stimuli share any features with the target stimulus, a condition that was explicitly stated in the task instructions. Although three features define the target stimulus, attention is needed to focus on only one of those features, as with the Easy task, to make a correct identification of the target. A final repetition of the Simple RT task then re-assesses baseline response times to examine if there were any changes in RT as a function of fatigue or a release from effortful attending.

The extensive behavioural research findings by Stuss and colleagues using this series of tasks identified: i) the negative effect of head injury on general processing speed and consistency of performance across multiple testing sessions, divided attention (Complex RT task), and focused attention (Redundant RT task) (Stuss et al., 1989a; 1989b), ii) the negative effect of aging on general processing speed with choice decisions and the disruption of focusing attention in the presence of irrelevant information (Stuss et al., 1989b); iii) the additional negative interaction effect of aging and head injury on processing speed and the improvement of performance consistency more than five years after injury (Hetherington et al., 1996); iv) the differential negative effect of focal frontal lesion location on general processing speed (maintaining intention to attend, superior medial frontal lobes), error production to specific types of stimuli (false positives relating to setting task rules, left frontal lobe), and all error types

relating to monitoring performance against those rules (right frontal lobe) (Stuss et al., 2002), and inconsistency of performance (Stuss, Murphy, Binns, & Alexander, 2003); and v) a lack of effect of focal lesions in non-frontal regions or different regions of the cerebellum on any these processes with the exception of increasing variability only in the most complex situations in people with non-focal frontal lesions compared to controls (Alexander, Gillingham, Schweizer, & Stuss, 2012; Stuss et al., 2002, 2003).

For this current set of studies, the FIT tasks and simultaneous EEG recordings were selected as a set of tools. Both are known to be sensitive to the identification and timing of separable attentional processes in response to varying task demands within one paradigm (and without the added requirement of localizing in space). Based upon previous literature, the combination of FIT and EEG was also hypothesized to be especially important because of the ability offered by the combination to address the gaps in the previous set of literature, namely:

- i) The measurement of non-auditory cognition (as a visual task),
- ii) The capture of subtle changes in attention (as a set of tasks tapping multiple processes combined with timing measures that capture pre-response activity) in people expected to be cognitively healthy,
- iii) The evaluation of basic and advanced levels of attentional complexity to assess if changes in cognition associated with age-related hearing loss are truly affecting non-auditory domains rather than just complex contexts where attention is re-directed to deal with hearing loss, and
- iv) The evaluation of early (in terms of time) sensory-attention interaction and the recruitment of hypothesized anterior (frontal lobe) processes to assess for compensatory versus declining visual attention processing in older adults.

General Hypotheses. It was generally hypothesized that the usage of a task paradigm known to be sensitive to measuring separable aspects of attention (especially involving anterior, or frontal, processing) in a hierarchical manner in combination with EEG analysis would reveal more specifically if and how vision-based cognitive processes are affected by age-related hearing loss.

- i) RT on the FIT task: all participants in these studies were recruited from a database where they self-identified as being cognitively and neurologically healthy, and after recruitment they were administered a battery of standard neuropsychological tests to ensure that they did not meet criteria for any form of cognitive impairment. The older adults with and without hearing loss were thus not expected to differ on standard neuropsychological measures. However, if hearing loss is associated with a change in vision-based cognitive processing then RT performance on the more sensitive FIT task was expected to differ between older adults with and without hearing loss dependent upon the types of attentional processes that are most affected. The variable results of previous research studies suggest two possible broad outcomes for the RT data. If older adults with mild hearing loss are experiencing cognitive decline in multiple sensory domains then their RT may be slower than older adults with age-typical hearing. By contrast, if older adults with mild hearing loss are relying more on their visual system to compensate for hearing loss and have more cortical area re-directed toward visual processing as seen in middle-aged adults with mild hearing loss, then their RTs may be similar or even faster than the older adults with age-typical hearing. Although brain imaging in a prior study of middle-aged adults with mild hearing loss revealed possible compensatory activity (Campbell & Sharma, 2014), this does not necessarily support a prediction that a behavioural outcome will be *better* than that of a control group without hearing loss. The few behavioural studies that exist in older adults with hearing loss have shown that they perform worse than older adults with age-typical hearing. It was therefore expected that similar results would be found here where the older adults with mild hearing loss would be slower compared to the older adults with age-typical hearing. However, a novel aspect of the current set of studies was to examine RT performance on tasks ranging in complexity. It was additionally hypothesized that the older adults with mild hearing loss would show slowing on RTs for all tasks, including on the relatively easier tasks and not just the more complicated tasks. This hypothesis is based on the idea that, if there is an expectation that the functioning of the visual-cognitive system is fundamentally altered by hearing loss, then the older adults with mild hearing loss would show changes in the whole scope of their visual attentional processing and not just in the reduction of their ability to handle the most complicated aspects of attention as the higher-order processes are used to resolve auditory processing difficulties.

Additional analyses of the RT other than those used in previous studies of the FIT tasks were planned to evaluate the functioning of automatic versus voluntary/strategic response preparation. It was expected that the older adults with mild hearing loss would show an alteration in their strategic aspects of processing if they are also strategically compensating for hearing loss through their visual cognitive system.

- ii) EEG measures of visual processing: the EEG components analyzed in these studies were chosen based upon questions generated from previous research relating to the compensatory versus declining functioning of extra-auditory cognitive processes in the context of hearing loss.

The N1 was chosen to represent the early interaction between bottom-up sensory information and top-down attentional guiding. Although it was hypothesized that the older adults with mild hearing loss would demonstrate slower RTs on the behavioural measurements from the experimental tasks, the N1 represents visual processing that is not necessarily connected to final behavioural output. The older adults with hearing loss may be relying more on visual processing in the context of auditory processing and may thus have maintained compensatory processing in the relatively early attentional stages as represented by the N1. It was therefore expected that the older adults with hearing loss would show shorter N1 latencies and larger N1 amplitudes compared to age-typical hearing older adults as was seen previously in middle-aged adults with hearing loss (Campbell & Sharma, 2014).

The distribution of the anterior compared to posterior P3 was chosen to represent the recruitment of attentional processes hypothesized to be related mostly to anterior/frontal lobe functions. In studies examining aging without consideration for sensory loss, older adults are known to recruit more frontal lobe resources during a cognitive task compared to younger adults (Spreng, Wojtowicz, & Grady, 2010), which is hypothesized to be represented by an increase in the P3 amplitude measured at anterior electrode sites compared to posterior sites. Guerreiro and Van Gerven's (2017) study showed exaggerated aging effects on behavioural tasks when hearing loss is not considered (i.e., aging effects may be largely driven by older adults with hearing loss if they can be identified within an older sample). Older adults with hearing loss were thus hypothesized to show higher

amplitudes measured from anterior electrode sites, reflecting the recruitment of more resources than older adults with age-normal hearing in order to compensate for hearing loss. Unlike the N1, if older adults require more recruitment of anterior (frontal) attentional processing for task completion, this may slow the latency of the P3. This would be expected if there is observable slowing on the behavioural RT data given that the processes underlying the P3 are occurring closer to the time of overt responding.

Chapter 2

General Methods

2 General methods

2.1 Participants

There were three groups of participants: 21 healthy younger adults (YN; 8 males; age: 20–30 years, $M = 23.3$, $SD = 3.3$; education: $M = 16.8$ years, $SD = 2.1$), 17 older adults with typical hearing thresholds for their age (ONHA; 3 males; age: 66–77 years, $M = 71.0$, $SD = 3.2$; education: $M = 15.9$ years, $SD = 3.3$), and 15 older adults with mild hearing threshold elevations (OHL; 8 males; age: 65–79 years, $M = 73.0$, $SD = 3.8$; education: $M = 16.3$ years, $SD = 3.3$). Six additional older participants with hearing loss were recruited but did not meet inclusion criteria (three due to an asymmetry in pure-tone thresholds between the left and right ear; two due to pure-tone threshold results that suggested that they had a hearing problem that was not related to aging such as wax; one due to a health-related condition that was not reported in the initial participant database that was used to identify potential participants). One older adult with hearing loss was excluded after participation due to falling asleep during task administration. Handedness was determined by asking participants to identify the hand that they used for common tasks such as writing and using a spoon. All participants were community-dwelling and recruited from the participant database at Baycrest Health Sciences, Toronto. Inclusion criteria based on self-report included good English fluency, right-handed, normal colour perception, no history of brain injury, and no history of environmental exposure to noise. The study protocol was approved by the Research Ethics Board of Baycrest Health Sciences and carried out in accordance with their recommendations. Informed written consent was obtained according from all participants in accordance with the Declaration of Helsinki.

2.2 Hearing

Hearing thresholds were measured for all participants and used to categorize the older participants into the ONHA and OHL groups. Those in the OHL group had pure-tone air-conduction thresholds obtained in a sound-attenuating booth using standard audiometric procedures that were in the range from 20 and 40 decibel hearing level (dB HL) for five test frequencies (250, 500, 1000, 2000, 3000 Hz) in each ear. Those in the ONHA group had thresholds below 20 dB HL at each of the five test frequencies in each ear, but some had higher

thresholds at 4000 or 8000 Hz. For all participants, the inter-aural pure-tone threshold difference did not exceed 15 dB at any frequency. The audiometric results averaged for each group of participants are presented in Figure 1A.

2.3 Other sensorimotor measures

Other sensorimotor and cognitive measures were administered to describe characteristics of the participants that might influence their performance on the experimental tasks. These measures included a speech-in-noise test and a finger tapping test. Visual contrast sensitivity was also tested in older participants. The speech-in-noise test was the QuickSIN (Killion, Niquette, Gudmundsen, Revit, & Banerjee, 2004) whereby listeners repeated as much as possible of a series of sentences embedded in multi-talker babble presented via ear inserts (ER-3; Etymotic Research). Six sentences were presented at 65 dB HL in each of two equivalent conditions (using different sentences) in which the signal-to-noise ratio (SNR) decreased in 5 dB intervals from 25 dB to 0 dB SNR with each successive sentence. A SNR index accounted for the average number of critical words repeated across both conditions, with a lower SNR index representing better performance. The QuickSIN results averaged for each group of participants are presented in Figure 1B. Visual acuity of the older participants was assessed via the Mars Letter Contrast Sensitivity Test (Mars Perceptric Corp, 2003-2014) and results are presented in Figure 1C; visual acuity was not tested in younger participants. Given the hand-motor response (button press using two fingers of the dominant hand) required in the experimental task, basic finger tapping speed was assessed in each hand via a finger tapping test (Reitan & Wolfson, 1993), and results are presented in Figure 1D.

2.4 Self-ratings of everyday hearing abilities

Both groups of older adults were also given two self-report questionnaires that assessed the effect of hearing loss on daily functioning, the Hearing Handicap Inventory for the Elderly (HHIE; Ventry & Weinstein, 1982) and the Self Assessment of Communication Questionnaire (SAC; Schow & Nerbonne, 1982), with a higher score on the questionnaires indicating more problems. The results of these assessments are presented in Figure 1E.

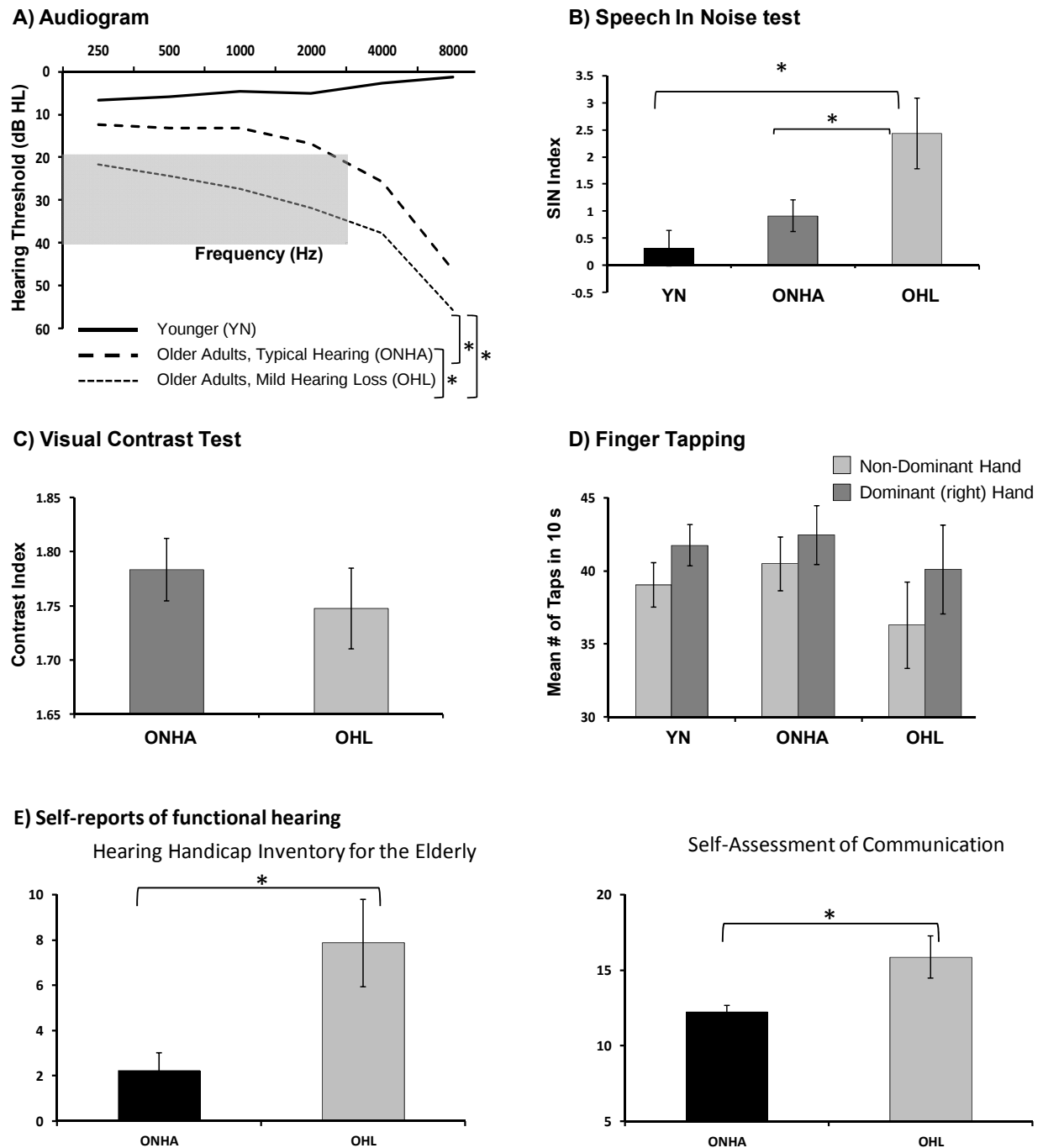


Figure 1: Indices of sensory and motor functioning. The asterisk (*) represents between group differences in performance. A) The group pure-tone averages (averaged across both ears). The grey area represents the criteria used to categorize mild hearing loss as audiometric thresholds falling between 20 – 40 dB HL from 250 – 3000 Hz. B) The Speech in Noise (Quick SIN) index of the amount of target information (words in a sentence) that could be correctly recognized in the context of an increasing amount of background noise (babble). A higher score represents

worse performance. C) The Mars Letter Contrast Sensitivity Test index of visual contrast calculated from the number of letters identified (accounting for errors) as the contrast between the target letters and the background gradually decreases. A higher score represents better functioning. D) The index of basic motor speed using a finger tapping test, in both hands, represented by the average number of taps produce in ten seconds. A higher score represents better functioning. E) Two indices of functional hearing ability: i) the Hearing Handicap Inventory for the Elderly (HHIE), indexing the social and emotional effects of hearing loss and the emotional reaction to the sensory loss, and the Self-Assessment of Communication (SAC) indexing the self-appraisal of the effect of hearing loss on communication abilities in different settings. In both measurements, a higher score represents a decrease in function/ability. YN, younger group; ONHA, older adults with age-typical hearing for their age; OHL, older adults with mild hearing loss.

2.5 Standard neuropsychological tests

The main experimental task was expected to utilize multiple cognitive processes including processing speed, attention, and working memory. Thus, a comprehensive but brief neuropsychological battery was administered to all participants in order to provide a standardized measurement of these processes in a similar manner as had been done in previous research (Lin et al., 2013). The tests provided an index of functioning within cognitive domains, namely: processing speed (Trail Making Test A, Reitan & Wolfson, 1985, 1993; Stroop Word Reading, Stroop, 1935; Digit Symbol Coding, Wechsler, 1997a), visual (Spatial Span Forward, Wechsler, 1997b) and auditory (Digit Span Forward, Wechsler, 1997b) attention, visual (Spatial Span Backward, Wechsler, 1997b) and auditory (Digit Span Backward, Wechsler, 1997b) working memory, speeded visual executive processing (Trail Making Test B, Reitan & Wolfson, 1985, 1993; Stroop Colour Naming, Stroop Interference, Stroop, 1935), other executive functioning (Phonemic fluency, Newcombe, 1969, and Semantic fluency, Benton, 1968; CVLT-II interference Trial B, Delis, Kramer, Kaplan, & Ober, 2000), visual memory (Digit Symbol Incidental Learning, Wechsler, 1997a), and verbal memory (CVLT-II Total Recall on 5 Learning Trials, Short-Delay Free Recall, Long Delay Free Recall, Delis et al., 2000).

2.6 Experimental task

Figure 2 shows a schematic of the stimuli and presentation procedure. For each task, every trial had a single stimulus appearing in the centre of a black computer screen and required

a motor hand response with the dominant (right) hand only on a Psychology Software Tools serial response box. Stimulus presentation was controlled using E-Prime software (version 2.0). There were four different tasks, presented in the following sequential order and each with one continuous block of trials: Simple, Easy, Complex, Redundant, and Simple. The Simple task was administered twice, as the first and last tasks in the series. In the Simple task, participants pressed a button with their index finger in response to the appearance of every stimulus, which was always the same white-outlined square for all participants in both blocks of the task. In the Easy, Complex, and Redundant tasks, participants pressed one button with their index finger in response to the infrequent target (25%) and a second button with their middle finger in response to the non-targets (75%). Each task block began with a set of practice trials and on-screen instructions. All participants reached the threshold of 80% accuracy on the practice trials and proceeded to the experimental task. Following the practice trials, each block contained trials with randomized foreperiods (FPs, the wait time between the offset of one stimulus and the onset of the next stimulus) of four equally frequent lengths (3, 4, 6, or 7 seconds). There were 50 trials in each block of the Simple task and 100 trials in each block of the Easy, Complex, and Redundant tasks.

The stimuli in the Simple task (Figure 2A) consisted of a simple white-outlined square. Participants were instructed that they would see a white square appear on the screen and that their job was to press button number 1 as fast as possible when the square appeared. They were presented with five practice trials, and then reminded of the instructions before starting the task.

The Easy task (Figure 2B), occurred immediately after the first block of the Simple task. It used four white outlined shapes (square, cross, circle, triangle), one of which was randomly chosen by the software program as the target for each participant (the chosen target remained the same in the practice trials and all test trials). The participants were instructed that they would see circles, squares, crosses, and triangles, one at a time, and that their job was to press button number 1 as fast as possible whenever the target appeared and to press button number 2 as fast as possible whenever a non-target appeared. A screen next appeared that led the participants through an example of how to respond if a particular figure (a triangle) were designated as a target compared to how to respond if any other figure appeared. Participants were then presented with a screen on which their randomly-generated target appeared followed by ten practice trials.

They were then reminded of the instructions and their target (which remained the same as in the practice trials) before starting the task.

The Complex task (Figure 2C) used stimuli composed of the four same shapes as had been used in the Easy task, one of four colours (red, blue, yellow, green), and line fillings that were oriented in one of four possible directions (horizontal, vertical, slanting forward, slanting backward). The target stimulus was defined by a particular combination of the three features, with non-targets sharing 0, 1, or 2 features with the target. The participants were instructed that they would see objects one at a time that varied in shape, colour, and line filling. They were told that they would see the same four shapes as in the previous (Easy) task. They were then presented with a screen containing four circles in the four colours used in the task. They were asked to name the colours to ensure that they could accurately identify them. They were then presented with a screen of four squares, each one containing lines in one of the four possible orientations. A screen next appeared that led the participants through an example of how to respond if a particular figure (a blue square with horizontal lines) were designated as a target compared to how to respond if any other figure appeared. The next screen contained their randomly-generated target stimulus and they were then presented with ten practice trials. Following the practice trials they saw a screen reminding them of the instructions and their target stimulus, which was the same as in the practice trials. They then started the task.

The Redundant task (Figure 2D) used stimuli that were defined by three features as in the Complex task, but none of the non-targets shared any of the target's features. The procedure for the instructions in the Redundant task was the same as for the Complex task, with the exception of the explicit statement on the opening screen that, unlike the previous (Complex) task, none of the non-targets would share any of the features with the target stimulus.

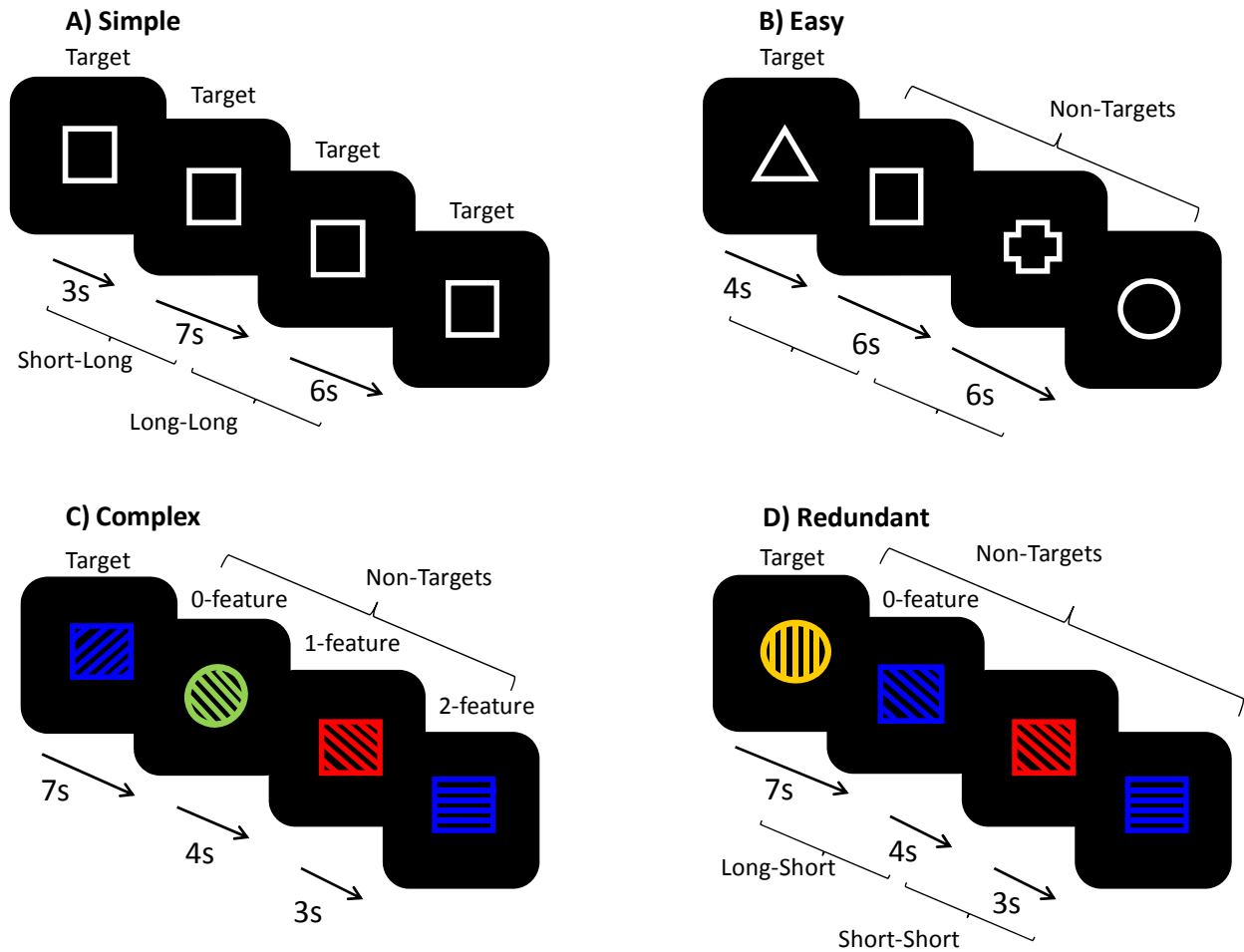


Figure 2: A schematic of the stimuli used in each task. (A) The Simple task used a single stimulus and required a single button press in response to each stimulus. (B) The Easy task was a binary choice task requiring one button press to the appearance of a pre-defined target (defined as a white outlined shape, 25% of trials), and a second button press to all other non-target stimuli (defined as three different white outlined shapes). (C) The Complex task was a binary choice task requiring one button press to the appearance of a pre-defined target (defined as a combination of a shape, color, and directional line filling, 25% of trials), and a second button press to all other non-target stimuli (defined by combinations of three features that share either 0, 1, or 2 features with the target). (D) The Redundant task was a binary choice task requiring one button press to the appearance of a pre-defined target (defined as a combination of a shape, color, and directional line filling, 25% of trials), and a second button press to all other non-target stimuli (defined by combinations of three features that were not shared with the target). The inter-trial intervals were either 3, 4, 6, or 7 s (seconds). For the foreperiod (FP) analyses (Chapter 3), trials with both 3 and 4 s FPs were combined to create the ‘short’ FP category and trials with both 6 and 7 s FPs were combined to create the ‘long’ FP category.

2.7 Procedure

The neuropsychological battery was administered on one day and the experimental task with EEG was administered on a subsequent day, with the exception of five participants who completed all tasks on the same day due to scheduling constraints.

The experimental task was conducted in an electrically-shielded sound booth, with participants sitting 90 cm from the 35 x 35 cm computer screen on which the 9cm-square stimuli that subtended visual angles of 5° were presented. For EEG recording, they were connected to a BioSemi Active recording system and had the Psychology Software Tools serial response box positioned comfortably under their right (dominant) hand. EEG recording took place during each of the five tasks, with a few minutes rest without EEG recording in between tasks. Participants were asked an open-ended question regarding the spontaneous strategies that they used to complete the task at the end of the experimental task.

2.7.1 Electrophysiological recording and analysis

Neuroelectric activity was continuously digitized using a BioSemi Active Two system (BioSemi V.O.F., Amsterdam, the Netherlands) with a bandpass of 0.16-100 Hz and a sampling rate of 512 Hz, recording from a 66 electrode array, grounded by an active Common Mode Sense (CMS) and a passive Driven Right Leg (DRN) passive electrode. Ten additional electrodes were placed below the hair line (both mastoid points, both pre-auricular points, outer canthus of each eye, inferior orbit of each eye, two facial electrodes) to monitor eye movements and to cover the whole scalp evenly. The average of all scalp EEG channels was used as the reference for each EEG channel) for ERP analyses. Data were subsequently analyzed using Brain Electrical Source Analysis software (BESA, version 6.1; MEGIS GmbH, Gräfelfing, Germany).

For the Simple RT tasks, a 1000-ms epoch included 200 ms of pre-stimulus activity and 800 ms of post-stimulus activity. For the binary choice tasks, a 1400 ms epoch included 200 ms of pre-stimulus activity and 1200 ms of post-stimulus activity (the ERPs were time locked to the onset of the stimulus). For each task, and for each participant and electrode site, ERPs were averaged separately for trials with correct responses to target or non-target presentations (and for

the multiple types of non-targets in the Complex task). Data were analyzed by referencing an average of all electrodes and was computed off-line.

For each participant, the continuous EEG data was first digitally filtered at a low cut-off of .53 Hz forward and 6 dB octave. Blinks and saccades create potentials that have different scalp topographies due to the differences in the ways that they are generated (i.e., eyelid sliding over the positively charged cornea to create blink potentials or a change in orientation of the corneoretinal dipole create saccades, Picton et al., 2000), and there can be significant intra-individual differences in their generation. Ocular movements assessing blinks and vertical and horizontal saccades were therefore recorded for each participant before and after the experimental task to calculate average eye movement components representing blinks, and lateral and vertical movements (Picton et al., 2000). These components were used to detect and subtract scalp projections from the electrophysiological data to minimize ocular movement contamination.

2.8 Data analysis

The dependent measures and statistical analysis for each study are described in the following respective chapters.

Chapter 3

Changes in Multi-sensory and Attentional Functioning in Older Adults with Hearing Loss

This chapter is a reformatted version of a manuscript published in *Frontiers in Aging Neuroscience*.

Gillingham, S.M., Vallesi, A., Pichora-Fuller, M.K., & Alain, C. (2018). Older adults with hearing loss have reductions in visual, motor and attentional functioning. *Frontiers in Aging Neuroscience*, 10, doi: 10.3389/fnagi.2018.00351.

Abstract

Evidence from epidemiological, laboratory, and clinical research suggests a link between age-related auditory declines and domain-general cognitive declines. Nevertheless, few studies have experimentally compared measures of non-auditory cognitive functions in younger normal hearing adults (YN), older adults with typical hearing thresholds for their age (ONHA), and older adults with clinically significant threshold hearing loss (OHL). The current study investigated the differences between these groups on measures of attentional response selection and execution to visual stimuli. A visual reaction time (RT) paradigm involving four tasks with differing hierarchical attentional demands was administered. RTs on trials with differing foreperiods (pre-stimulus waiting times) were analyzed to assess context-related slowing, error commission and related cognitive control, and strategic and automatic neural preparatory processes. The OHL group demonstrated a general slowing that was most apparent on the simplest tasks. Although the number of errors was similar when comparing all three groups, the OHL group exhibited less control over recovery from an error compared to the younger and ONHA groups. Unlike the YN and ONHA groups, the OHL group also showed difficulties with both strategic and automatic response preparation, although automatic preparation was more affected across all tasks. This pattern of results suggests that in older adults with hearing loss there is an underlying difficulty in automatic temporal processing that can affect higher order cognitive functions, although there may not be a completely generalized decline in cognitive functioning that is associated with hearing loss.

3 Changes in multi-sensory and attentional functioning in older adults with hearing loss

3.1 Introduction

This first study intended to further characterize the relationship between hearing loss and potentially extra-auditory cognitive functions by analyzing the behavioural outcome measures of the visual tasks in the FIT paradigm. In addition to the measurements that have been examined in previous research using the FIT (RT, number of errors, and the RT on trials surrounding an error trial), the analysis of the foreperiod effect was used to assess the automatic and strategic (voluntary) aspects of response preparation that underlie the final behavioural outcomes.

The foreperiod (FP) as defined by the tasks used in the current study is the time interval between the offset of one stimulus due to a response and the onset of the next stimulus. Analysis of RT as a function of the length of the FP provides insight into the internal pre-response preparations that underlie a person's readiness to attend before responding once the imperative stimulus appears. Evidence suggests that a decline in these preparatory processes contributes to age-related slowing (Kolev, Falkenstein, & Yordanova, 2006). Further examination of the FP using both simple and easy binary choice RT tasks similar to those used in this study has shown that there may be at least two aspects of response preparation, one strategic or somewhat voluntary and another that is more automatic. One outcome measure of response preparation, called the variable FP (v-FP) effect, refers to faster response speed as the length of the FP increases in blocks of trials with multiple lengths of foreperiods (Drazin, 1961; Karlin, 1959; Woodrow, 1914; and reviewed in Niemi & Näätänen, 1981). However, the RT on a given trial is also influenced by the FP that occurred in the preceding trial, labeled the sequential FP (s-FP) effect (Karlin, 1959; Woodrow, 1914), which presents as an asymmetrical distribution of RT dependent upon the trial-to-trial combination of relative FP lengths. In healthy adults, the asymmetry is characterized by slower RT on trials where the FP of the preceding trial is longer than the current trial, in comparison to trials where the preceding FP is either the same or shorter than the current FP.

Regardless of the type of task used, the v-FP effect is typically interpreted as resulting from a strategic evaluation of the passing of time throughout the FP, such that the longer the FP the more likely (i.e., the higher the conditional probability) that the stimulus will appear and the more ready the participant is to respond to the incoming stimulus (Näätänen, 1970). Stuss et al. (2005) showed that the benefit associated with the lengthening of the FP is markedly reduced in patients with right frontal lesions, suggesting that the right prefrontal cortex plays an important role in strategic time monitoring. However, this conditional probability account does not explain asymmetric s-FP effects and the equal benefit of a preceding short FP when the current trial's FP is also of an equally short duration. Several theories have been proposed to explain the association between the v-FP and s-FP effects. Los and colleagues (Los, Knol, & Boers, 2001; Los & van den Heuvel, 2001) proposed a single process account, which assumes that there is an inherently dependent relationship between the two effects due to the automatic nature of temporal estimation. Alternative accounts based on lesion and developmental studies suggest that the v-FP and s-FP effects represent independent and separable versus preparation processes (Stuss et al., 2005; Vallesi et al., 2007a; Vallesi & Shallice, 2007b; Vallesi, Arbula & Bernardis, 2014).

In this study, RT, error commission and error-related RT, and the v-FP and s-FP effects were used to assess for the functioning of visual attentional processes in response to differing task demands in younger adults with normal hearing (YN), older adults with normal hearing for their age (ONHA), and older adults with mild hearing loss (OHL). In particular, RT was examined as a function of the FP effect to assess if there were differential changes in underlying automatic versus strategic response preparatory processes in relation to hearing loss that may be above and beyond normal aging. We hypothesized that there may be alterations in sensitive measures of visual attention and response readiness as a function of hearing ability, which would further corroborate the links between hearing loss and general non-auditory cognitive functioning. Based upon previous research in older adults (e.g., Guerreiro & Van Gerven, 2017), RT was expected to be slower in the OHL group compared to the ONHA group, over and above age-related slowing. Moreover, if the functioning of the visual-cognitive system is fundamentally altered by hearing loss then the OHL group would be expected to show slowing regardless of task complexity. However, given the possibility that the members of the OHL group may rely more on visual processing to compensate for hearing loss, it was expected that they may show an

alteration in the strategic aspects of response preparation if they are also strategically depending more on their visual cognitive system although the exact nature of change is difficult to predict based upon past research. While most previous findings have focused on a disruption of strategic preparatory processes resulting in an increase in RT as a foreperiod of the currently relevant trial increases, the OHL group may actually display faster RTs than the ONHA group in this context if they have a greater reliance on visual processing.

3.2 Methods

3.2.1 Participants

All three groups of participants were involved in this study: 21 healthy younger adults (YN), 17 older adults with typical hearing thresholds for their age (ONHA), and 15 older adults with mild hearing threshold elevations (OHL).

3.2.2 Measures

Standard neuropsychological measures

A sub-set of the neuropsychological tests was used to assess processing speed, simple attention, and working memory in order to provide a standardized measurement of these processes in a manner similar to previous research (Lin et al., 2013). The tests included the Trail Making Test (parts A and B; Reitan & Wolfson, 1985), Digit Symbol Coding (Wechsler, 1997a), Digit Span Forward and Backward (Wechsler, 1997b), and Spatial Span Forward and Backward (Wechsler, 1997b). The Trail Making Test part A is a measure of focused attention and speed using visual language-based stimuli (digits), and part B has an additional executive component involving the continuous switching between concepts (i.e., alternating between numbers and letters while putting each string in sequence). Digit Symbol Coding is a measure of speeded and focused attention using visual stimuli only. The forward subscales of the Digit and Spatial Span tests measure auditory and visuospatial simple attention, respectively. The backward subscales of each test measure auditory and visuospatial working memory.

Experimental task

The FIT was administered to all participants as outlined in the general methods.

3.2.3 Outcome variables

The first outcome variable analyzed was the average RT. Average RTs from all correct trials were calculated across all trial types combined in the Simple and Easy tasks, and for each trial type (target vs. non-target) for the Easy, Complex, and Redundant tasks. Each participant's trials were examined for RTs that fell below 150 ms for exclusion purposes, but none occurred. The second outcome variable was the number of errors. The number of errors was tabulated per stimulus type (target and non-target) in the Easy, Complex, and Redundant tasks. The third outcome variable was the RT of the correct trials both preceding and following an error trial in the Easy, Complex, and Redundant tasks.

Finally, RTs were additionally analyzed according to four categories of trial-to-trial sequential combinations of FP lengths: i) current short and previous short lengths (short-short), ii) current short and previous long lengths (short-long), iii) current long and previous short length (long-short), and iv) current long and previous long length (long-long). 'Short' was defined as FPs of either 3 or 4 seconds, and 'long' was defined as FPs of either 6 or 7 seconds. The FP analyses were carried out for only the Simple, Easy, and Redundant tasks. The RT data from the Complex task was not included in this analysis because it was thought that the higher order cognitive processing required for this task could interfere with the detection of automatic and strategic preparatory activity.

3.2.4 Data analysis

All analyses were carried out initially using the sensory (visual contrast) and motor functioning (finger tapping) measurements as covariates. Since the resulting pattern did not change when covariates were included, the results without the covariates are presented.

Scores on the neuropsychological tests were analyzed separately in one-way ANOVAs to evaluate differences between groups.

All RT variables were first analyzed across all tasks in an omnibus repeated measures ANOVA. For the RT and number of errors, they were each first compared across the two repetitions of the Simple tasks in a 2 (task repetition) x 3 (group) mixed ANOVA.

Dependent upon the presence of interaction effects, RTs were analyzed in several sequential stages as described below to evaluate if they were affected by the hypothesized attentional demands introduced for each task. RTs were compared between the first Simple task and the overall Easy task (all trial types included) in a 2 (task) x 3 (group) mixed ANOVA to assess for the effect of the introduction of a basic choice on RT. On the choice-based Easy, Complex, and Redundant tasks, a 3 (task) x 2 (trial type, target and non-target) by 3 (group) mixed ANOVA was conducted to determine if there was an effect of context complexity on RT when participants were confronted with choice. For the Complex task, only the 0-feature non-target and the target stimuli were included so that there would be two types of trials as in the other two tasks. The error-related RT was analyzed in a 3 (task) x 3 (trial type) x 3 (group) mixed ANOVA.

The FPs were analyzed using ANOVAs with 2 (task) x 2 (current FP, short versus long) x 2 (previous FP, short versus long) x 3 (group) for combinations of tasks, including the two repetitions of the Simple task, the first Simple task and the Easy task, and the Easy and Redundant tasks. The comparison of the first and second Simple RT tasks was used to assess changes in response preparation as a function of time on task and possible fatigue (tonic arousal). The comparison of the Simple tasks to the Easy task was used to assess changes in response preparation as a function of a slight increase in attentional requirements. The comparison of the Easy and Redundant tasks was used to assess changes in response preparation as a function of the presence of more stimulus information in the Redundant task (shape, colour, line filling) compared to the Easy task (shape only). Bonferroni corrections were applied to pairwise comparisons.

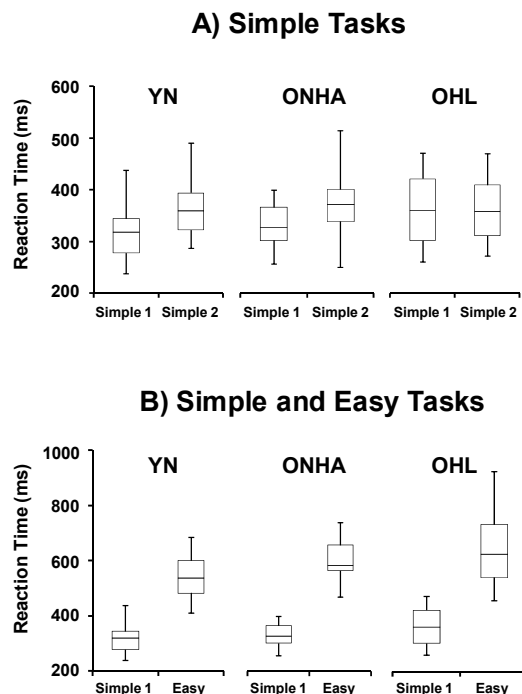
3.3 Results

3.3.1 Neuropsychological results

There were no significant differences between groups on the Digit Span Forward or Backward tests. Younger adults performed significantly better than both older groups on the Trail Making Test A [faster RT, $F(2,50) = 5.84, p = .005, \eta_p^2 = .19$], Trail Making Test B [faster RT, $F(2,48) = 4.96, p = .01, \eta_p^2 = .17$], Digit Symbol Coding [greater number of matched digits-to-symbols, $F(2,50) = 40.32, p < .001, \eta_p^2 = .62$], Spatial Span Forward (larger span, $F(2,50) = 6.32, p = .004, \eta_p^2 = .20$], and Spatial Span Backward [larger span, $F(2,50) = 13.14, p < .001, \eta_p^2 = .35$]. The two older groups did not differ significantly from one another.

3.3.2 RT results

Figure 3 shows the mean RT for each task. In the omnibus ANOVA, there was a significant interaction of group and task [$F(8,184) = 6.85, p < .001, \eta_p^2 = .23$]. This interaction was further examined in the separate ANOVAs examining the tasks in more detail.



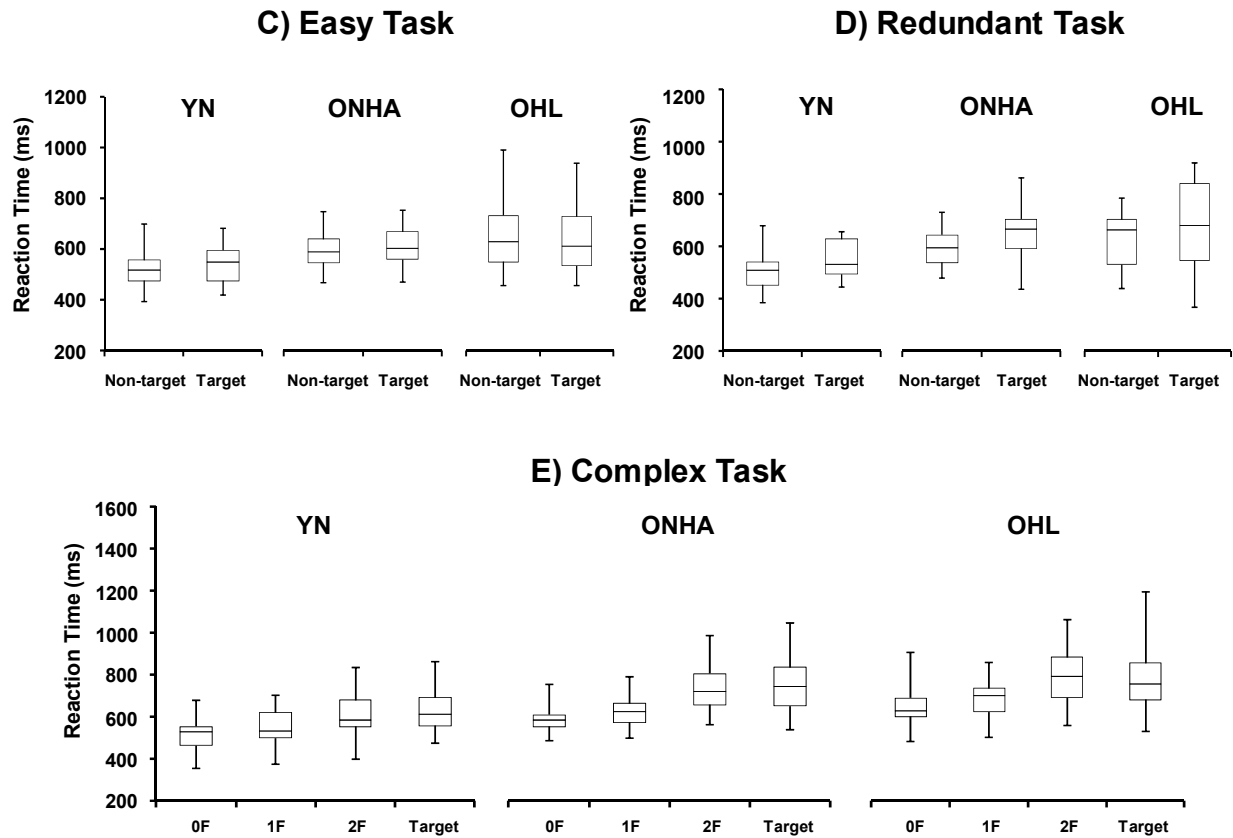


Figure 3: Box plot diagrams showing the RTs for: A) both the Simple RT tasks (the first application of the task is labeled as Simple 1 and the second as Simple 2), B) the first Simple task and the Easy task, and then separated by stimulus type for the: C) Easy, D) Redundant, and E) Complex tasks. 0F, 1F and 2F refer to the non-target stimuli in the Complex task that share either 0, 1, or 2 features, respectively, with the target. YN, younger group; ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

Simple tasks. RT in the Simple task condition was slower for the second compared to the first task administration [$F(1,49) = 25.70, p < .001, \eta_p^2 = .34$]. However, a significant interaction between group and task administration highlights that this slowing did not occur equally for all three groups [$F(2,49) = 4.03, p = .02, \eta_p^2 = .14$]. A one-way ANOVA comparing the change score (the second minus the first administration) illustrated that the YN group had a larger difference between the two administrations compared to the OHL group (pairwise, $p = .03$). The ONHA group's difference score did not differ from either group but was closer to the YN group's mean. The second administration of the Simple RT task was approximately 50 ms

slower than the first for the YN and ONHA groups, whereas it was only 6 ms slower for the OHL group.

Simple versus Easy tasks. Introducing a choice into the task slowed RTs for all groups, as shown by a main effect of task in the comparison of the first Simple RT task and the Easy RT task [all target and non-target stimuli included, $F(1,48) = 637.63$, $p < .001$, $\eta_p^2 = .93$]. However, the pattern of RT slowing from the first administration of the Simple task to the Easy task was not the same for all groups [task x group interaction: $F(2,48) = 5.56$, $p = .007$, $\eta_p^2 = .19$]. Pairwise comparisons in the ANOVA of the change scores to examine the interaction [Easy task, all stimuli included, minus the first administration of Simple task: $F(2,50) = 5.56$, $p = .007$] revealed that the YN group demonstrated less slowing from Simple to Easy compared to the OHL (pairwise, $p = .008$) group. The amount of slowing from Simple to Easy for the ONHA group fell in between the YN and OHL groups, and did not differ significantly from the YN group (pairwise, $p = .053$). The two older groups did not differ significantly (pairwise, $p = .74$).

Effects of choice and task context. The ANOVA comparing the responses to target and non-target trial types across the three choice-based tasks (Easy, Complex, Redundant) revealed a main effect of group [$F(2,47) = 6.84$, $p = .002$, $\eta_p^2 = .23$], with younger adults being faster than ONHA (pairwise, $p = .04$) and OHL (pairwise, $p = .003$) older adults, who did not differ significantly from each other. The main effect of task was also significant [$F(2,94) = 26.28$, $p < .001$, $\eta_p^2 = .36$]. Overall, participants had slower RTs on the Complex task than on the Easy (pairwise, $p < .001$) and Redundant tasks (pairwise, $p < .001$). A main effect of trial type [$F(1,47) = 56.85$, $p < .001$, $\eta_p^2 = .55$] revealed slower RTs to the target than the non-target trials. However, the group variable did not interact with either task or trial type.

Summary of behavioural RT data. The OHL group exhibited a general slowing that was apparent on all tasks, especially on the Simple RT task where, unlike the YN and ONHA groups, they demonstrated a slowing on the first administration and then an absence of change from the first to the second administration of the task. Adding a choice component to the response criteria using basic shapes as stimuli (comparing Simple and Easy RT) elicited slowing that was greater for the OHL group compared to the YN group (the ONHA group had an intermediate RT). In the comparison of all three choice-based tasks, there was a general slowing experienced by both

older groups in comparison to the YN group, and all groups responded more slowly to the target than to the non-target stimulus, regardless of task context.

3.3.3 Error results

Overall, few errors were made. The total number of errors did not significantly differ between the three groups, and are depicted in Figure 4A-C. There was a larger number of false negative compared to false positive errors (responding to an infrequent target as though it were a non-target) for all three groups, as shown in the main effect of error type [$F(1,47) = 14.99, p < .001, \eta_p^2 = .24$].

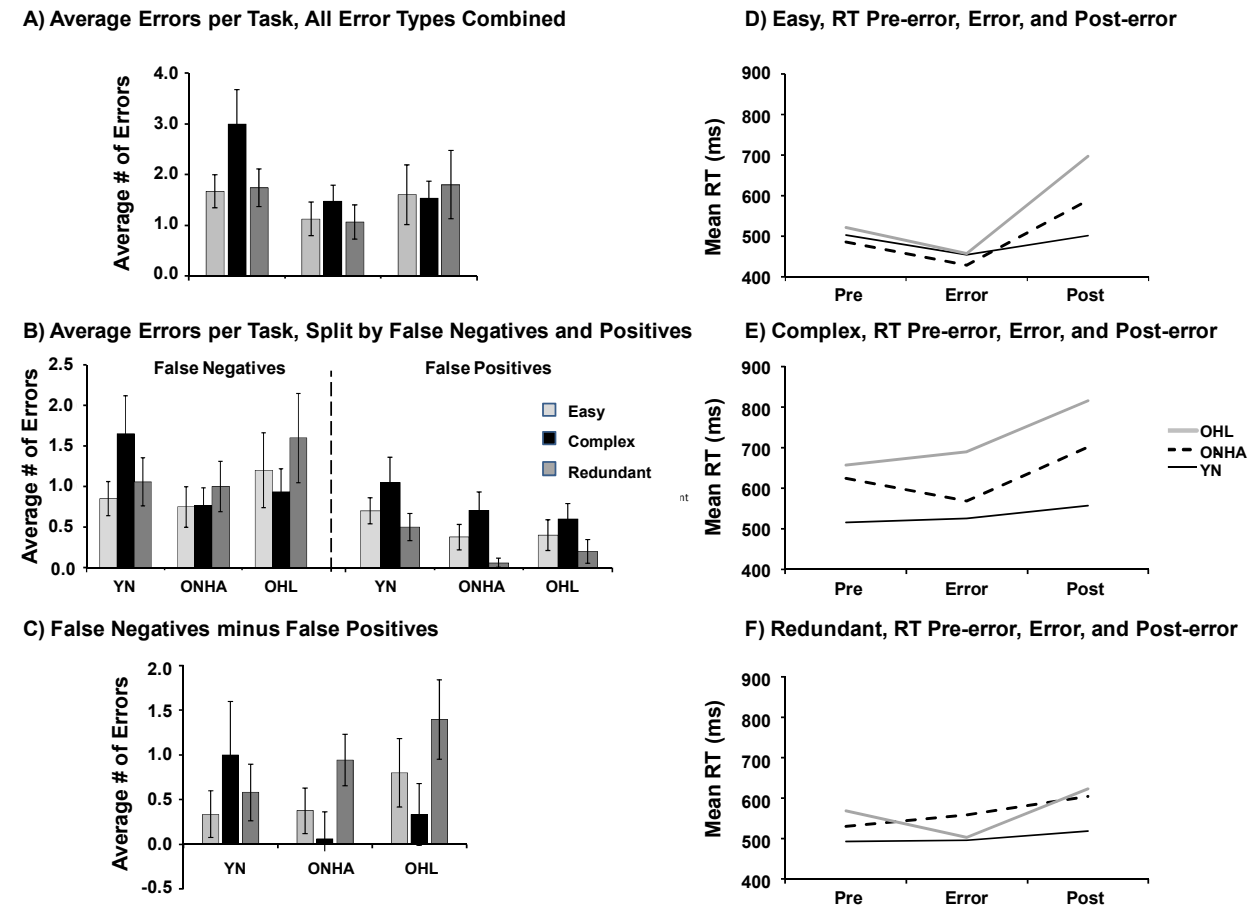


Figure 4: Illustrations for the average number of errors (panels A–C) and the RT on error trials and on correct trials preceding and following the error trials (panels D–F). Panel (A) shows the average number of errors of all types combined for each task. Panel (B) shows the average number of errors for each task, split by FNs and FPs. Panel (C) shows the difference between the two types of errors (FN minus FPs) for each task. Panels (D) to (E) show the RT for the trial preceding an error, the error trial, and the trial following an error for each task. FP, false positive;

FN, false negative; YN, younger group; ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

Error-related RT was examined by evaluating the RT on error trials and on the trials immediately preceding and following the error trials, and is depicted in Figure 4D-F. An omnibus ANOVA comparing RT across these three trial types across all three tasks indicated that the groups differed in their RT as a function of task [task x group interaction: $F(4,46) = 3.64$, $p = .01$, $\eta_p^2 = .24$] and by trial type [trial type x group interaction: $F(4,46) = 3.51$, $p = .01$, $\eta_p^2 = .23$]. Follow-up analyses examined group differences in each task separately. In the Easy task, a main effect of trial type [$F(2,60) = 22.73$, $p < .001$, $\eta_p^2 = .43$] showed that the post-error trial had a slower RT compared to both the pre-error and error trials (pairwise, $p < .001$). A trial type x group interaction [$F(4,60) = 4.63$, $p = .003$, $\eta_p^2 = .24$] was further investigated by performing separate ANOVAs on change scores calculated for the pre-error RT (pre-error RT – error RT) and post-error RT (error RT – post-error RT). There were no group differences on the pre-error RT calculation. As shown in Figure 4D, a group x RT change interaction for the post-error RT calculation [$F(2,30) = 7.51$, $p = .002$] illustrated that the YN group's post-error change in RT was significantly smaller than that of the OHL group (pairwise, $p = .002$). The ONHA group also showed slowing on the post-error trial, but the RT cost was of an intermediate value that did not significantly differ when compared to the YN and OHL groups. In the Complex task, again a main effect of trial type [$F(2,72) = 6.50$, $p = .003$, $\eta_p^2 = .15$] showed that the post-error trial RT was slower than both the pre-error (pairwise, $p < .001$) and error (pairwise, $p = .021$) trials. The trial type x group interaction was not significant as there was post-error slowing for all three groups. However, the main effect of group was significant [$F(2,36) = 8.76$, $p = .001$, $\eta_p^2 = .33$]. As illustrated in Figure 4E, the OHL group had an overall RT across all trials that was significantly higher than the YN (pairwise, $p = .001$). The ONHA group had an intermediate RT that did not significantly differ from either group. For the Redundant task, the difference between trial types was less pronounced for all three groups (Figure 4F), and the post-error RT was only slightly higher than the pre-error trial RT (the difference was not statistically significant).

Summary of errors. There were more false negative errors than false positives for all three groups, and this difference between error types was slightly larger in the Redundant task compared to the Easy task. With respect to RTs related to errors, the post-error trials elicited a slower RT compared to the pre-error and error trials for all groups for almost all tasks. In the

Easy task, the OHL group showed greater post-error slowing compared to the YN, while the ONHA group had an intermediate amount of post-error slowing. The Complex task elicited post-error slowing in all three groups, although the OHL group was slower across all three trial types compared to the YN and the ONHA group showed an intermediate RT. There was a weak indication of post-error slowing for all three groups in the Redundant task, but there were no significant group differences.

3.3.4 Foreperiod effect results

Figure 5 shows the group mean RTs in the various FPs for each task. An initial omnibus ANOVA involving four tasks (first and second administrations of the Simple task, Easy task, Redundant task) revealed the presence of the expected FP effects. RT was faster when the current FP was relatively longer, showing the v-FP effect [main effect of the current FP: $F(1,46) = 45.68, p < .001, \eta_p^2 = .50$]. RT was also faster when the previous trial's FP was relatively shorter than the current trial's FP, showing the s-FP effect [main effect of the previous FP: $F(1,46) = 58.51, p < .001, \eta_p^2 = .56$]. The s-FP effect was modulated according to the length of the previous FP, where relatively longer previous FP's produced a slower RT, showing the asymmetrical nature of the s-FP effect [current x previous FP interaction: $F(1,46) = 24.24, p < .001, \eta_p^2 = .35$]. Interaction effects between the foreperiod, task, and group variables for the current FP [task x FP x group: $F(6,138) = 3.12, p = .007, \eta_p^2 = .12$], previous FP [task x FP x group: $F(6,138) = 2.17, p = .05, \eta_p^2 = .09$], and asymmetrical effects [task x current FP x previous FP: $F(3,138) = 3.68, p = .01, \eta_p^2 = .07$] showed modulation of the classic FP effects as a function of group membership and task context.

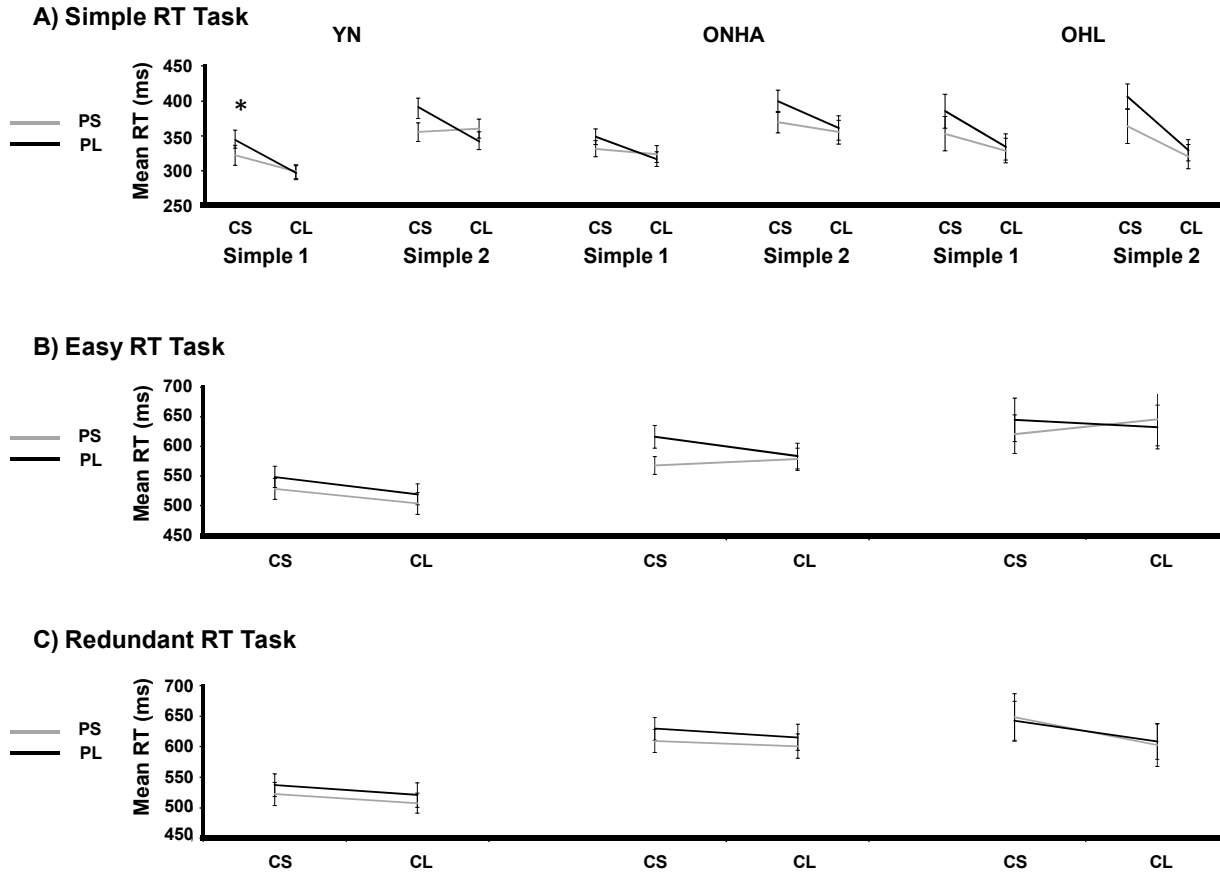


Figure 5: Illustrations of the v-FP and s-FP effects for the: A) Simple, B) Easy, and C) Redundant tasks. CS, Current Short FP; CL, Current Long FP; PS, Previous Short FP; PL, Previous Long FP; Simple 1, the first administration of the Simple task; Simple 2, the second administration of the Simple task; YN, younger group; ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss. Refer to the top, left-most figure* (Simple 1 for the YN group) for an illustration of the most typical of all types of foreperiod effects (variable effect, v-FP; sequential effect, s-FP; asymmetric s-FP). The typical v-FP occurs when response time (RT) on trials with a current long FP is faster than trials with a current short FP. The typical s-FP effect occurs when RT is faster on trials that follow trials with a relatively shorter FP. The asymmetric FP effect occurs when the trial-to-trial FP combination of current short-previous long has the overall slowest RT compared to all three other trial-to-trial FP combinations.

Simple tasks. Comparing the two administrations of the Simple RT task (Figure 5A), the main effect of the current FP was significant [$F(1,49) = 57.55, p < .001, \eta_p^2 = .54$], showing the classic v-FP effect of a faster RT on trials that have a longer current FP. The main effect of the previous FP was also significant [$F(1,49) = 33.15, p < .001, \eta_p^2 = .40$], showing the basic s-FP effect of faster RTs when a previous trial had a short FP. The current x previous FP interaction

was also significant [$F(1,49) = 23.30, p < .001, \eta_p^2 = .32$], illustrating the asymmetric aspect (longer RT when the previous trial's FP is longer than the current trial's FP) of the s-FP effects. Unlike the YN and ONHA groups, the OHL group had a slower RT on trials that had a short current FP whereas their RT on trials that had a long current FP was almost exactly the same across both tasks (i.e., there was more of a cost to RT when the current FP was short, although the interaction was non-significant, $F(2,49) = 2.91, p = .06, \eta_p^2 = .11$).

Effects of choice and task context. In the comparison of the Simple and Easy tasks, there were again the expected main effects representing the classic v-FP [main effect of current FP: $F(1,48) = 24.98, p < .001, \eta_p^2 = .34$], s-FP [main effect of previous FP: $F(1,48) = 29.25, p < .001, \eta_p^2 = .38$], and asymmetry of the s-FP [current x previous FP interaction: $F(1,48) = 23.15, p < .001, \eta_p^2 = .33$] performance patterns were observed.

A task x current FP interaction [$F(1,48) = 7.11, p = .01, \eta_p^2 = .13$] illustrated that the difference between the current short and long FPs was smaller in the Easy task (longer FP faster by 10.6 ms) than in the Simple task (longer FP faster by 31.3 ms) when all three groups were considered together. The task x previous FP x group interaction was significant [$F(2,48) = 4.29, p = .02, \eta_p^2 = .15$]. As illustrated in Figures 5A and 5B, the OHL group did not benefit from having a relatively short FP on the previous trial compared to the current trial in the Easy task as it did in the first Simple task, unlike the YN and ONHA groups.

Effects of interfering information in the task context. In the comparison of the Easy and Redundant tasks, again the expected main effects were present, showing the classic v-FP pattern [main effect of current FP: $F(1,47) = 15.79, p < .001, \eta_p^2 = .25$], s-FP pattern [main effect of previous FP: $F(1,47) = 27.24, p < .001, \eta_p^2 = .37$], and asymmetry of the s-FP [current x previous FP interaction: $F(1,47) = 7.02, p = .011, \eta_p^2 = .13$]. The task x current FP x group interaction was significant [$F(2,47) = 4.60, p = .015, \eta_p^2 = .16$]. It indicated that the OHL group had a different response pattern for the short versus long current FPs across the tasks (Figures 5B and 5C). On average, the trials with a current long FP were faster than trials with a current short FP (the typical v-FP effect) in both tasks for the YN (Easy, long = 511 ms, short = 538 ms; Redundant, long = 514 ms, short = 530 ms) and ONHA (Easy, long = 589 ms, short = 600 ms; Redundant, long = 603 ms, short = 619 ms) groups. By contrast, for the OHL group, the RTs on trials with a current long FP were very similar, and actually slower, than on the trials with a current short FP

in the Easy task (long = 650 ms, short = 643 ms), but the results followed the same pattern as the other two groups in the Redundant task (long = 617 ms, short = 654 ms). That is, they returned to the typical v-FP effect in the Redundant task. Additionally, a previous FP x group interaction [$F(2,47) = 4.45, p = .02, \eta_p^2 = .16$] indicated that there was a difference between groups in the RT response that was dependent upon the previous trial's FP. Regardless of task, RTs on trials with a previous short FP were faster than on trials with a previous long FP (the typical s-FP effect) for the YN (Easy, previous short = 514 ms, previous long = 534 ms; Redundant, previous short = 515 ms, previous long = 529 ms) and ONHA (Easy, previous short = 580 ms, previous long = 610 ms; Redundant, previous short = 603 ms, previous long = 619 ms) groups. By contrast, the OHL group showed similar RTs to trials with previous short and long FPs in both tasks (Easy, previous short = 643 ms, previous long = 649 ms; Redundant, previous short = 636 ms, previous long = 636 ms). That is, they did not display a typical s-FP effect in either task.

Summary of foreperiod effects. In the comparison of the two administrations of the Simple RT task, the classic v-FP and s-FP effects, and the asymmetrical pattern of the s-FP effect were present for all groups. An interaction effect with the group, task, and current FP variables that trended toward significance indicated that the OHL group may have experienced a greater cost of RT when the current FP was relatively shorter, especially in the second repetition of the task. Notably, with the introduction of choice (comparison of the first Simple RT task and the Easy task), the OHL group, unlike both the YN and ONHA groups, did not benefit through a quickening of the RT on trials with a relatively shorter previous FP. In the two choice-based tasks (Easy and Redundant), the OHL group again did not benefit through a quickening of RT from having a relatively shorter previous FP, but they were able to regain their v-FP effect and respond faster on trials with a current long FP as opposed to no benefit to RT in the Easy task.

3.4 Discussion

The purpose of this study was to compare attentional processing in older adults with mild hearing loss (OHL) against that of older adults with age-normal hearing (ONHA) and younger adults (YN) both within and across visual RT tasks that increased in complexity, and thus in the requirement for attentional resources. The use of visual RT tasks allowed for the evaluation of extra-auditory cognitive changes that may be associated with hearing loss in aging, and the varying level of complexity allowed for the evaluation of the different levels of attentional

processing. Both older groups showed comparable performance, with expected age-related changes when compared to the YN group, on processing speed and attention as indexed by performance on neuropsychological tests. Importantly, using visual detection tasks that varied in attentional demands, we showed deficits in attention and response preparation processes in older adults with mild hearing loss that were not observed in younger or older adults who had better hearing thresholds. The findings for the OHL group indicate that there may be underlying disruptions in some cognitive processes that span multiple sensory and cognitive domains, but do not necessarily represent a generalized decline in global functioning.

3.4.1 General slowing and impairments in self-guided engagement

The first overall observation from the data is that of general slowing demonstrated by the OHL group compared to both the YN and ONHA groups. However, this group-specific slowing was more noticeable in the Simple RT and Easy RT tasks than on the Complex and Redundant tasks. Furthermore, the OHL group showed an unusual pattern of performance across administrations of the Simple RT task. While the YN and ONHA groups showed the expected increase in RT from the first to the second repetition of the task, the RT of the OHL group was a little slower on the first administration than the RT of the other two groups and their RT did not change from the first to the second administration.

Simple RT has been previously reported to be somewhat resistant to the cognitive effects of aging and general slowing (Salthouse, 1985; Stuss et al., 1989b; Welford, 1980). The unusual findings for the OHL group in the current study could reflect difficulty in the initial strategic or voluntary effort required for all higher-order attentional processes, which Stuss and colleagues defined as energization (Stuss et al., 2002, 2005; reviewed in Stuss & Alexander, 2007). The previous findings reported by Stuss and colleagues in studies of patients with brain lesions involving damage to specific dorsomedial frontal lobe regions have been interpreted as evidence of a disruption in this effort system (Stuss, 2011; Stuss et al., 2002; Stuss & Alexander, 2007). The results observed in the OHL group were more subtle than the findings reported in lesion studies insofar as the unusual effects for the OHL group were limited to tasks that depended on mostly self-driven sustained attention (Simple and Easy RT tasks but not the Complex and Redundant tasks) and could indicate a problem attending when the tasks are somewhat easy and monotonous. Also, the almost equivalent performance between the two administrations of the

Simple RT task is not apparent in any previous publications in patients using this FIT task, or in unpublished data in a group of healthy people of similar and older age than the current sample, or other similar tasks (Stuss et al., 2005). One possible explanation of this finding to consider is age-related slowness in motor output, especially given that it has been shown to affect simple RT (Woods, Wyma, Yund, Herron, & Reed, 2015) and the non-significant slowing of the non-dominant hand by the OHL group in this study. However, the participant's hand-motor responses as measured by single-finger tapping in the hand that was used to make the response was equivalent across the three groups, although was more variable for the OHL group. Additionally, the statistically significant findings on the RT measures remained significant when the finger-tapping scores were used as a covariate. Comparatively, although the OHL group is still generally slower than the YN and ONHA groups on the more difficult Complex and Redundant tasks, the OHL group showed more differentiation between trials types on these tasks than in their performance on the easier tasks. On these latter two tasks, their slowest responses occurred to the target stimulus, although they had a little more difficulty in the most demanding scenario of differentiating between the target and 2-feature non-target in the Complex task. In these more difficult tasks, there is more stimulus information available which may seemingly drive the system to respond. The slowing from the first to the second administration of the Simple task for the YN and ONHA groups seems to represent a release from the effortful attending on the tasks of intermediate difficulty or possibly fatigue. For the OHL group, however, the lack of change in RT from the first to the second administration of the Simple task suggests that there may not have been as big of a change in the amount of effort, or drive, to the system with the introduction of choice and additional stimulus features, and that perhaps the system was already working at the optimal pace.

Another possibility to consider is that this type of pattern (i.e., a somewhat general slowing on easier tasks in contrast to more typical responding on more complex tasks) in performance is similar to what is occasionally observed in populations with affective disorders, especially depression. Many theories expect cognitive performance in people with depression to decline as attentional requirements increase, due to either reduced cognitive capacity (Hasher, Rose, Zacks, Sanft, & Doren, 1985; Hasher & Zacks, 1979), or the narrowing of attentional focus. By contrast, some studies have shown improved performance with increasing attentional demand (Hertel & Rude, 1991; Krames & McDonald, 1985), including variations on simple RT

tasks (Thomas, Goudemand, & Rousseaux, 1999). However, there is a limit to the improvement as people with depression performed worse than controls when there was a decision or choice (Thomas et al., 1999). One interpretation of the improvement in performance with some increase in attentional demand is the sudden utilization of attentional or executive resources that were previously utilized by thought processes related to the affective disorder while the person performed the easier task, and this implies that there was not just a general slowing with depression. In the current study, such an interpretation of distracted attentional resources would not perfectly apply to these older adults with hearing loss because performance is not fully improving on more difficult tasks, but instead there appears to be more engagement of attention when more stimulus information is involved. However, it does suggest that, in these older adults, there may be some general underlying difficulty with their ability to engage attention on their own or when discrimination is difficult, but still have the attention/executive resources to show more engagement when the opportunity arises.

3.4.2 Executive impairments in response bias and control

Their error commissions and subsequent recovery provides some evidence that the OHL group had difficulty on the more demanding tasks. Overall, they did not commit more errors than the other two groups, and it was also observed that error commission did not vary with age. The YN group also showed more errors (in the Complex task) than the older groups. However, the OHL group generally committed more false negative errors across most tasks, and they had more error and post-error slowing on the Easy and Complex tasks. This suggests that even though they may have been more engaged with these stimuli that had more information to process in the relatively more difficult tasks, the increase in false negative errors can represent a response bias and a difficulty in switching from the more common response (responding that an item was a non-target was expected 75% of the time) and they had more difficulty with controlling their recovery from making errors in such a demanding context as contained within the Complex task.

3.4.3 Mechanisms of response preparation

The nature of the slowing in attentional processes was examined through the analysis of the RTs as a function of foreperiod (FP) length. In the Simple RT tasks, for all three groups, the classic effects of v-FP (shorter RTs on trials with longer FPs), s-FP (shorter RTs when the

previous trial's FP was shorter than the current trial), and the asymmetric nature of the sequential FP effect (longer RTs when the previous trial's FP is longer than the current trial's FP) were present. However, the OHL group experienced slowing when the current trial's FP was short, whereas they were able to respond nearly as quickly as the other groups on trials with a current long FP, and they maintained this ability across tasks. They were actually a little faster on the current long FP trials in the second administration of the Simple task but, especially in comparison to the YN group, they experienced a greater cost (longer RT) on trials that had a current short but a previous long FP.

According to theories that try to explain differences in the underlying processes of the v-FP and s-FP, when the current trial's FP is short, automatic processes related to motor arousal determine the relative RT dependence upon the previous trial's FP. If the previous trial's FP is short, then there is a facilitation effect whereby phasic arousal is increased and the RT will be approximately the same as the RTs on the current long FP trials. However, if the previous trial has a relatively long FP, then there is a temporal refractory period at the motor level that delays responding, and creates the asymmetric nature of the s-FP effect (Vallesi et al., 2007a; Vallesi & Shallice, 2007b). Across repeated administrations of the Simple RT tasks, the YN and ONHA groups demonstrated a shift of their entire distribution of RTs across all FP combinations, reflecting a general slowing from the first to the second task. The slowing for the OHL group, however, appeared consistent across both administrations of the Simple task. This slowing was reflected in difficulty reacting on trials where there was a relatively short FP, and this was exacerbated when the previous trial had a relatively longer FP. This pattern of difficulties related to the length of the FP suggests that participants with mild hearing loss are able to strategically monitor the passage of time when the current FP is relatively long and they are not necessarily affected by changes in tonic levels of arousal. However, they may experience difficulty with the more automatic neural preparatory activity that is responsible for phasic levels of arousal and motor preparedness.

With the introduction of choice, the OHL group did not benefit from having a previous short FP as did the YN and ONHA groups, which generally maintained a consistent pattern of performance across the different FP combinations in all tasks. The YN group had a reduced asymmetry in their s-FP effect in the Easy task because they did not seem to experience as high of a facilitation effect on short-short FP trial combinations. Additionally, in comparing the two

choice tasks (Easy and Redundant), the OHL group again did not benefit from having a previous short FP in the Redundant task, but these participants were able to have faster responses on trials with a current long FP in the Redundant task compared to the Easy task. The YN and ONHA groups demonstrated the typical FP effects that have been previously shown using both simple and easy choice tasks (Vallesi, Lozano, & Correa, 2014). The change in the OHL group's performance across tasks, however, suggests that there was an increase in the attention of these older adults to the stimulus identity and selection that significantly altered preparatory abilities. In the transition from the Simple to the Easy task, the increase in cognitive demand changed their ability to rely on the automatic timing aspects that are thought to underlie the sequential effects, but also caused their strategic timing preparatory abilities to be less effective (the disappearance of the v-FP effect). The Redundant task, however, used stimuli that contained much more identifying information (shape, colour, line orientation), and the OHL group again experienced disruptions in their automatic timing abilities but were able to engage their strategic timing abilities to a greater degree as shown in the return of their v-FP effect.

3.4.4 Source of response preparation deficits in aging and hearing loss

The next question of interest would involve accounting for the source of the difficulty of the automatic preparation processes in the OHL group, and to identify why there may be a reduction in this ability. The previous studies on dissociations of the automatic and strategic processes have looked at either brain injury to specific regions that would identify a distinct process (Stuss et al., 2005; Vallesi et al., 2007a) or at the development of these processes at a young age, examining when they actually appear for the first time (Vallesi & Shallice, 2007b). The lesion studies have identified cortical areas that are necessary to the typical functioning of these processes (right frontal region for the v-FP effect and left premotor regions for the s-FP effect). For the OHL group, however, there may not necessarily have to be a disruption in a specific cortical area (and it would be difficult to explain why their left premotor region would be particularly affected). Also, a cortical-based disruption in just pure automatic motor preparation would suggest that the same pattern of findings should have appeared across all tasks, whereas the OHL group here show selective effects based upon attentional demand. In the context of the findings on other tasks in this study, such as apparent ceiling RT effects on easy tasks and the increased engagement on more difficult tasks, and even those findings that show

non-significant group differences (slight reductions in visual contrast, slight reductions in non-dominant finger tapping), which can be disrupted at multiple points throughout a distributed motor system (Prigatano & Borgaro, 2003), and the reduction in hearing ability, suggests that there may be common underlying neural preparatory processes that are affected in this group. Auditory-based temporal processing is considered a key aspect to successful cognitive performance (Fogerty, Humes, & Kewley-Port, 2010) and speech understanding (Vaughan, Storzbach, & Furukawa, 2008) in aging. This current study suggests that there may be underlying disruptions in temporal processing that can be measurable in non-auditory tasks as well. An early hypothesis of mechanisms that underlie the hearing loss-cognitive decline relationship posited a common cause, such as a general neural degeneration underlying both sensory and cognitive decline in tandem (Baltes & Lindenberger, 1997; Humes et al., 2013; Lindenberger & Baltes, 1994). Rönnberg and colleagues (2011, 2014) suggested that their findings of differential influence of hearing loss on performance on different types of memory tests (long-term more than short-term) is evidence of a selective (rather than general) mechanism that connects hearing loss (more so than vision loss in their case) to specific types of cognitive decline. The results from this current study may not necessarily support a full common-cause association between cognitive and sensory decline. Similar to the results from the Rönnberg et al. studies, deficits are not completely generalized, at least in this very mild stage of hearing loss in a healthy sample of participants.

If the pattern of results here is meaningfully related to some form of underlying disruption in neuronal functioning, it could be hypothesized that such disruptions involve changes in white matter integrity and cortical volume that have been associated with age-related hearing loss. However, there is still much to be investigated with respect to the age of the person at time of the onset of hearing loss and the health of neuronal tracts outside of the auditory system (reviewed in Mudar & Husain, 2016). Changes in white matter integrity might be expected to have an even greater general effect that would have affected the OHL group's level of tonic arousal as well. Another possibility is a disruption earlier in the pathway affecting overlapping areas for sensory and motor information transfer and integration, such as the thalamus (Cappe, Rouiller, & Barone, 2009).

Chapter 4

Event-Related Potentials as a Function of Task Complexity: Evidence for Separable Attention Processes

This chapter is a reformatted version of a manuscript in preparation for *Canadian Journal of Experimental Psychology*.

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Abstract

Attention tasks can tap multiple processes depending upon the context established by the stimuli and task instructions. Based upon this idea, the Feature Integration Task was developed by Stuss and colleagues (Stuss et al., 1989a,b, 2002) to assess, across four different reaction time tasks, separable processes as they were recruited with changing attentional requirements. The purpose of the current study was to use electroencephalography and source modeling to measure the influence of task context (stimulus and task instruction) on the modulation of a marker of endogenous attention during the evaluation of incoming sensory information (the N1) and on the scalp distribution of a marker of the recruitment of hypothesized anterior (frontal lobe) attentional processes for stimulus categorization and preparation for response (the P3) in healthy young adults. The latency and amplitude of the N1, the posterior-anterior distribution of P3 amplitude and latency, and neural activity modeling supported an increasing reliance on anterior attentional processes, and some late-stage memory processing in the case of target selection, as tasks required either an enhancement or suppression of attention for stimulus discrimination. Variables that represented the ability to suppress attention were correlated with performance. The results from this study help to assess the timing and localization of separable attention-related processes as a function of task context within a single task paradigm, which may provide more specificity in outcome measures for further investigations assessing fluctuations in attentional functions.

4 Event-related potentials as a function of task complexity: Evidence for separable attention processes

4.1 Introduction

In the absence of a complete disruption of an attention network due to, for example, injury as studied in neuropsychological cases, it can be difficult to assess characteristics of different attentional processes from just the analysis of a behavioural task. Yet as interest grows in assessing changes in cognition during the early stages of clinical syndromes such as neurodegenerative diseases in aging, more sensitive metrics of slight shifts in attention will be required. Electroencephalography (EEG) can be helpful in identifying the timeline of attentional functioning. This second study intended to characterize event-related potentials (ERPs) evoked during the administration of the FIT task. The ERP components were selected a priori for their known representation of the early integration of bottom-up sensory and top-down attentional processes (the N1) and the relatively later separation of higher-order attentional processes involved in stimulus evaluation (anterior P3, especially hypothesized to be recruited from the frontal lobes) and categorization and response preparation (posterior P3). In particular, the hypothesized changes that would occur in these selected components as a function of changes in task demands was predicted to provide outcome metrics of timing and quantification of an amount of change in attentional processing that occurs with the sequential tasks within the FIT paradigm. The current study aimed to characterize these electrophysiological correlates of changes in attention relating to early sensory processing and relatively later recruitment of attentional (especially anterior) processes in young adults to provide outcome metrics that may be sensitive to clinical contexts where subtle changes in sensory and cognitive (especially frontal lobe) functioning are expected such as the early stages of hearing loss with aging.

Two commonly studied scalp-recorded ERP markers of attentional processing that can be measured without the requirement of a spatial component to the stimulus (as with the stimuli in the FIT task) in the visual domain are the N1 and P3 waves. The N1 occurs between 100 – 200 ms post-stimulus presentation, at approximately 170 ms. It represents early visual discriminative

processing and the interaction between the analysis of incoming stimulus information (exogenous influence) and the guiding, or orientation, of attention to task-relevant information (endogenous influence) (Eimer, 1998; Hillyard & Anllo-Vento, 1998; Mazza & Brignani, 2016; Williams et al., 2016). The N1 latency and amplitude are often measured as representations of the processing time required for stimulus feature discrimination and the amount of attention guided toward task-relevant information (Rorden, Guerrini, Swainson, Lazzari, & Baylis, 2008), respectively. The P3 peaks anywhere between 300 and 1000 ms in response to task-relevant events. In young adults, the P3 is largest over the parietal scalp region. It is thought to represent multiple functions including the attentive evaluation of a stimulus, categorization of an event to prepare for a response, or updating memory after categorization (Cycowicz & Friedman, 1997; Daffner et al., 2011; Kok, 2001; Polich, 2007; Sutton, Braren, Zubin, & John, 1965). Although different variations of the P3 have been elicited to different stimuli, such as a separate ERP in the presence of a novel and unexpected stimulus (Cycowicz & Friedman, 1997), a change in the P3 amplitude distribution measured from posterior versus anterior electrode sites (i.e., increasing amplitudes at anterior sites and/or decreasing amplitudes at posterior sites) has been hypothesized to represent the online recruitment of different brain regions required for a given task, especially those related to frontal lobe involvement, either due to inefficient processing in aging (Reuter, Voelcker-Rehage, Vieluf, Lesemann, & Godde, 2016) or recruitment of different processes based upon task demand (Daffner et al. 2011; Friedman et al., 1997; Friedman, Ritter, & Snodgrass, 1996). The recruitment of frontal brain regions during cognitive tasks is most often studied in aging, but has also been supported by fMRI studies in young adults that show increasing frontal activation with increasing working memory load (Cappell, Gmeindl, & Reuter-Lorenz, 2010; Mattay et al., 2006). The N1 and P3 were therefore predicted to be sensitive markers to detect subtle changes in separate attentional processes involving sensory processing and frontal lobe involvement within one paradigm (FIT) as a function of task complexity. Additionally, source models were statistically compared to estimate if task context (i.e., stimulus and instruction) engaged distinct brain regions.

It was hypothesized that changes in the latency and amplitude of the N1 and P3 would be modulated as changes in task demands recruited new attentional processes. The N1 latency and amplitude would both increase as the stimulus gained more information to be processed. It was also hypothesized that the P3 amplitude distribution would change from posterior to anterior

sites, with the largest overall amplitude as well as the most even distribution due to an increase at anterior sites occurring in response to the most challenging task demands. For source estimation, if the changes in the ERP modulations represent the recruitment of different attentional processes, then separable neural generators would be identifiable in the comparison of source estimations across tasks with a greater reliance on frontal regions as complexity increased. These detectable changes in markers of cognitive-sensory integration and the recruitment of frontal resources with small changes in demands to attention will provide metrics for understanding subtle changes in attention in early stages of clinical contexts without detectable behavioural or functional change.

4.2 Methods

4.2.1 Participants

The Young group only (21 healthy younger adults; YN) was involved in this study.

4.2.2 Measures

The FIT paradigm was administered to all participants as outlined in the general methods.

4.2.3 Procedure

The procedure for task administration and the collection and processing of the EEG data was as described in the General Methods section. In addition, for this dataset we used Classical LORETA (Low Resolution Electromagnetic Tomography) Analysis Recursively Applied (CLARA, BESA version 6.1) to estimate source activity during each task. This distributed source modeling approach estimates the total variance of the scalp-recorded data. It uses a smoothness constraint, which ensures that current changes little between adjacent regions in the brain. In the present study, the voxel size in Talairach space was 7 mm and the regularization parameters, which account for the noise in the data, were set at 0.01% singular value decomposition. The source analysis was performed at each time point. The source solution was inspected visually for several time points and was considered stable if the dominant source remained constant over 30 ms interval (i.e., 15 ms before and after the peak). The results are displayed on a standard MRI from BESA (version 6.1).

4.2.4 Data analysis

N1 – The interaction between attention and visual sensory information

The effects of stimuli and task on the N1 were quantified at posterior electrode sites over the left (P5, P7, P07) and right (P6, P8, P08) hemispheres. The window to capture the peak latency was 130 – 230 ms following stimulus presentation, and the mean amplitude was calculated as ± 40 ms surrounding the extracted peak latency.

The first set of analyses involved the N1 peak latency and mean amplitude to assess task-related differences in early visual discrimination dependent on task context. Repetitions of the Simple RT tasks were compared in a 2 (task) x 2 (hemisphere) x 3 (electrode) ANOVA to assess changes in simple baseline responding before and after effort attending on the more difficult tasks. The effect of task demands was assessed by comparing the three choice-based tasks on amplitude and latency via a 3 (task: Easy, Complex, Redundant) x 2 (stimulus: non-target, target), x 2 (hemisphere) x 3 (electrode) ANOVA. Only the 0-feature non-target and target stimuli were included from the Complex task to be the most equivalent comparison to the stimuli found in the Easy and Redundant tasks. The effect of stimulus complexity was assessed in the Complex task using a 4 (stimulus) x 2 (hemisphere) x 3 (electrode) ANOVA.

P3 – Stimulus evaluation and categorization

Following previous research on the distribution of the P3, this deflection was measured at midline electrode sites (i.e., Pz, Cz, and Fz) for the Easy, Complex, and Redundant tasks (these choice-based tasks involved stimulus categorization properties that are thought to be represented in the P3). Given the long latency range of the P3 and the possibility of inter-individual and inter-task variability, mean amplitudes were calculated for six time windows of 50 ms each from 300 ms to 600 ms after stimulus onset. The development of the P3 wave could then be more accurately traced over time for each stimulus in each task separately at each of the three electrodes. The time window with the largest amplitude was then extracted as the size of the peak (labeled the peak mean amplitude, Reuter et al., 2016) for each task, stimulus, and participant.

The latency of the peak amplitude (the time window during which the peak occurred) was first examined for the purpose of identifying if there was an interaction between the time window and electrode site (i.e., does the latency differ between the anterior and posterior electrode sites) by comparing the six time windows across electrodes in a 3 (task: Easy, Complex, Redundant) x 2 (stimulus) x 6 (time window) x 3 (electrode) ANOVA. Again, for the Complex task, only the 0-feature non-target and target stimuli were included. To assess for the effect of within task stimulus complexity, the latency of the peak was assessed in just the Complex task using a 4 (stimulus) x 6 (time window) x 3 (electrode) ANOVA.

Differences in P3 amplitude were then assessed first for the effect of task demands via a 3 (task) x 2 (stimulus) x 3 (electrode) on the peak mean amplitudes, followed by a 4 (stimulus) x 3 (electrode) repeated measures ANOVA to assess for the effect of stimulus complexity in just the Complex task alone. To assess if there was a change in the P3 amplitude distribution with a focus on posterior and anterior electrode sites as a function of task demands, a 3 (task) x 2 (stimulus) ANOVA was applied to the P3 gradient (Pz – Fz), followed by a one-way repeated measures ANOVA comparing the gradient for the 4 stimuli in the Complex task. Significant differences as a function of task or stimuli on the analyses of the gradient were further assessed at Fz and Pz electrode sites separately via mixed ANOVAs that accounted for the task and stimulus variables. This allowed for the examination and confirmation of differences at each end of the gradient that may be contributing to a change in slope without concern for comparisons across locations given the care required for interpretations of such findings in ERP research (Keil et al., 2014).

Source modeling

Statistical comparisons of CLARA source estimates calculated for each individual participant at time points relevant to the N1 and P3 for each of the choice-based tasks were calculated using BESA Stats (version 2.0). Based upon results from analysis of the N1 and P3 waveforms and the potentially different attentional processes elicited by specific stimuli, directed comparisons were planned to assess the effect of unnecessary and distracting information on the selection of a frequent non-target and an infrequent target (comparing the Easy and Redundant tasks via t-test on the source modeling for each stimulus separately), and to assess the effects of increasing similarity of non-targets to the target stimulus (comparing all four stimuli via repeated measures ANOVA in the Complex task).

4.3 Results

4.3.1 ERP results

N1 – The interaction between attention and visual sensory information

Figure 6 shows the group mean ERPs for each task and stimulus.

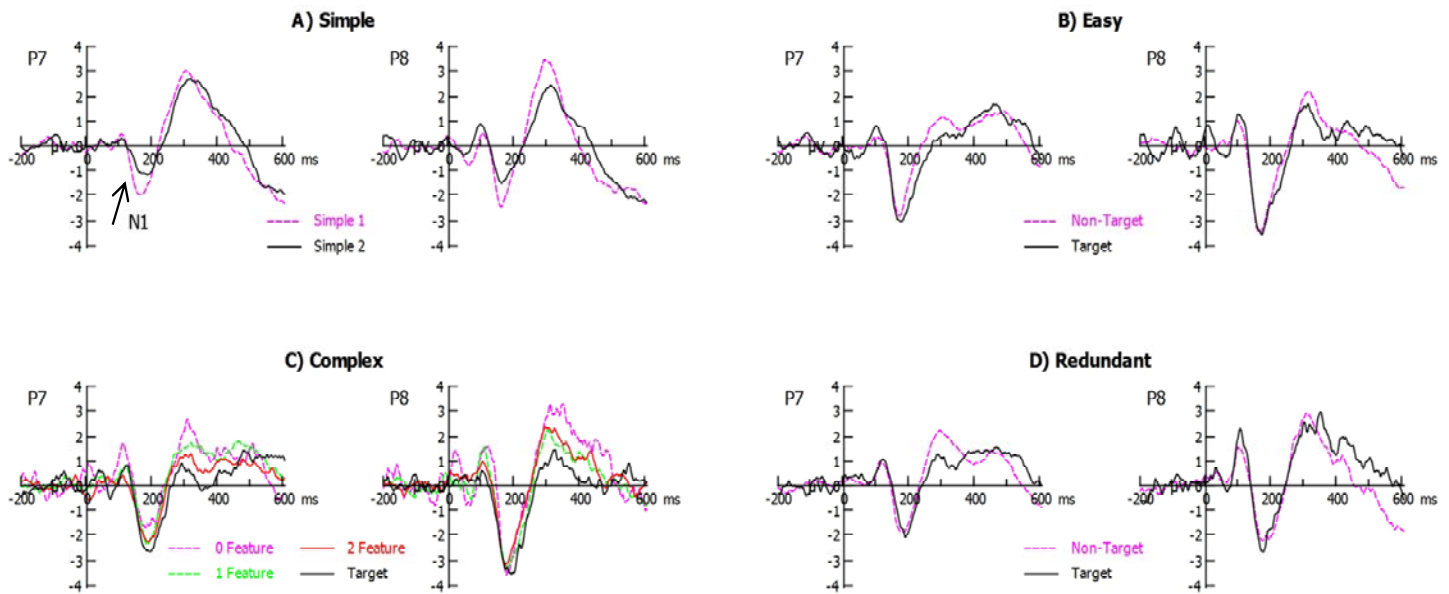


Figure 6: Group mean event-related potentials (ERP) waveform for the N1 for each task and stimulus measured from posterior parietal electrode sites, using electrodes P7 and P8 as an illustrative example. Negativity is downward going.

N1 Latency

The change in baseline responding over task repetitions: When comparing the repetitions of the Simple RT task, there was no difference in their peak N1 latency.

The effect of task demands: The N1 latency in the Easy task was shorter (166 ms) than both the Complex task (173 ms) and the Redundant task (176 ms) [main effect of task: $F(2,36) = 5.90$, $p = .006$, $\eta_p^2 = .25$], but only significantly differed from the Redundant task ($p = .001$). Overall, target stimuli had a slightly longer N1 latency (173 ms) than the non-target stimuli (170 ms) [$F(1,18) = 8.25$, $p = .01$, $\eta_p^2 = .31$].

The effect of stimulus complexity: In the assessment of the stimuli in the Complex task only, there were no significant differences between the four different stimuli on N1 latency.

N1 Amplitude

The change in baseline responding over task repetitions: As can be seen in Figure 6A, the mean N1 amplitude was less negative (smaller) in the second task compared to the first [main effect of task: $F(1,20) = 11.14, p = .003, \eta_p^2 = .36$].

The effect of task demands: Similar to the latency, the N1 amplitude in the Easy task was significantly greater than the Redundant task ($p = .04$), and the Complex task had an intermediary amplitude [main effect of task: $F(2,36) = 4.46, p = .02, \eta_p^2 = .20$]. Overall, the target stimuli tended to elicit larger N1 amplitude than the non-target, although the difference did not reach significance [$F(1,18) = 3.06, p = .097, \eta_p^2 = .12$]. For the Complex task, the target stimulus generated a larger mean N1 amplitude compared to the 0-feature non-target in this analysis, whereas in the Easy and Redundant task the two stimulus types were associated with almost equal N1 amplitudes.

The effect of stimulus complexity: In the assessment of the stimuli in the Complex task only, there were no significant differences between the four different stimuli on mean N1 amplitude.

Summary of the N1: The N1 amplitude was attenuated in the second repetition of the Simple RT task compared to the first with no changes in latency. In the choice-based tasks, the Easy task had the shortest latency and the largest amplitude, which significantly differed from the Redundant task. This was followed by the Complex and then Redundant tasks (in both amplitude reduction and increasing latency), which did not significantly differ from each other. Latency was longest in response to the target stimulus in all tasks.

P3 – Stimulus evaluation and categorization

Figure 7 shows the grand averaged P3 waveforms at Fz, Cz, and Pz for each task.

Latency of the peak amplitude of the P3 at anterior and posterior electrode sites

The P3 latency was assessed by identifying the 50-ms time window in which the peak amplitude occurred. The effect of task demands and stimulus complexity on this peak amplitude was evaluated by examining the interaction terms of task and stimulus with the time window variable.

The effect of task demands: Task type did not interact with the time window at which the peak occurred, meaning that the latency of the P3 peak was generally the same regardless of the task for these young adults. Overall, the P3 peak latency occurred earlier, in the 350 – 400 ms time window (Figure 8), at the Fz electrode site compared to the Cz and Pz electrodes [time window x electrode interaction: $F(10,180) = 2.02, p = .03, \eta_p^2 = .10$]. As can be seen in Figure 8, there was variability in the latency of the peak for different stimuli at the Pz but not Fz electrode [stimulus x time window x electrode interaction: $F(10,180) = 12.20, p < .001, \eta_p^2 = .40$]. Follow-up ANOVAs at Pz and Fz separately showed that the latency of the P3 peak amplitude for the target stimuli occurred later (400 – 450 ms) than for most of the non-target stimuli (350 – 400 ms) at Pz only [stimulus x time window interaction: $F(5,90) = 6.93, p < .001, \eta_p^2 = .28$].

The effect of stimulus complexity: Similarly in the analysis of the stimuli in the Complex task alone, latency of the P3 peak amplitude for the different stimuli differed according to electrode site [stimulus x time window x electrode interaction: $F(30,600) = 4.79, p < .001, \eta_p^2 = .19$]. At Pz alone the peak occurred later for the target and 0-feature non-target stimuli compared to the other two non-target stimuli [stimulus x time window interaction: $F(15,300) = 3.80, p < .001, \eta_p^2 = .16$].

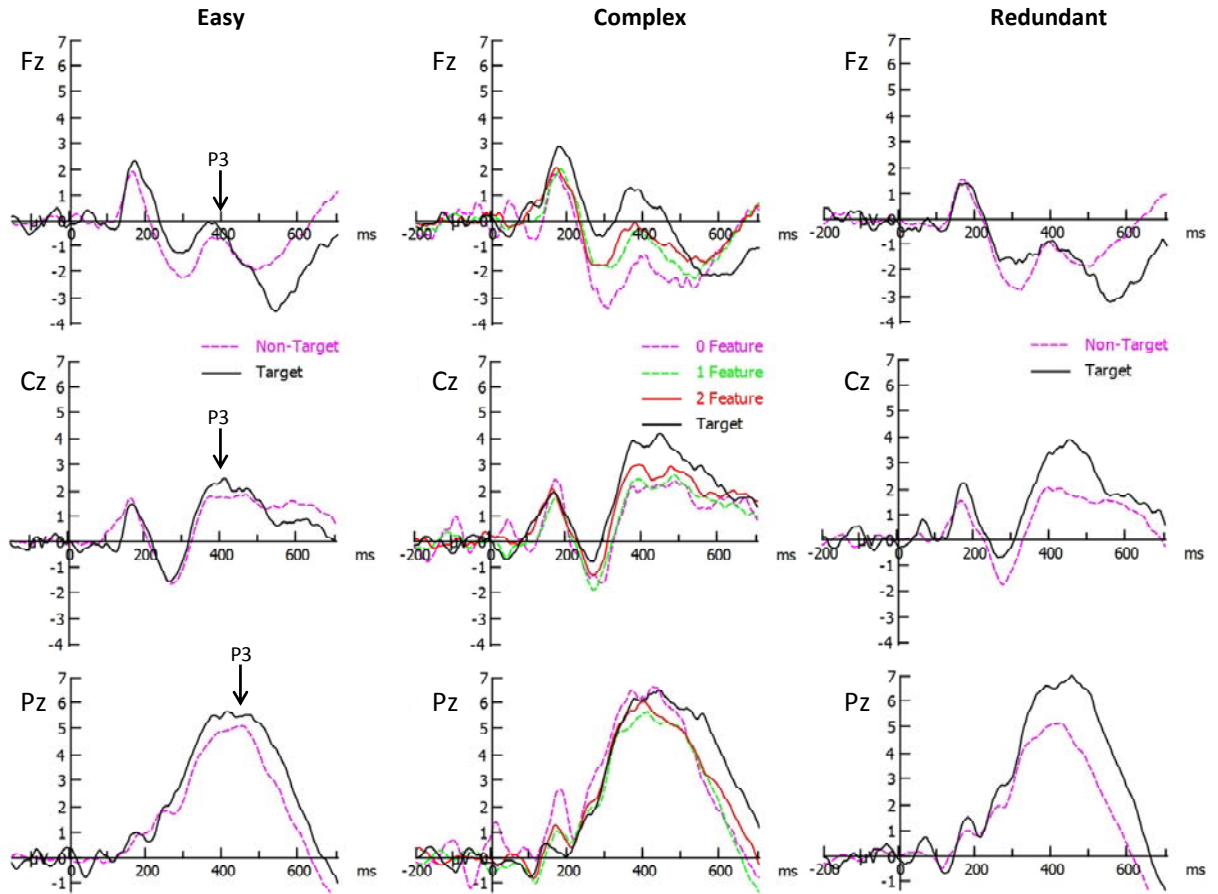


Figure 7: The grand averaged ERP waveform for the P3 at electrode Fz, Cz, and Pz for the Easy, Complex, and Redundant tasks. Negativity is downward going.

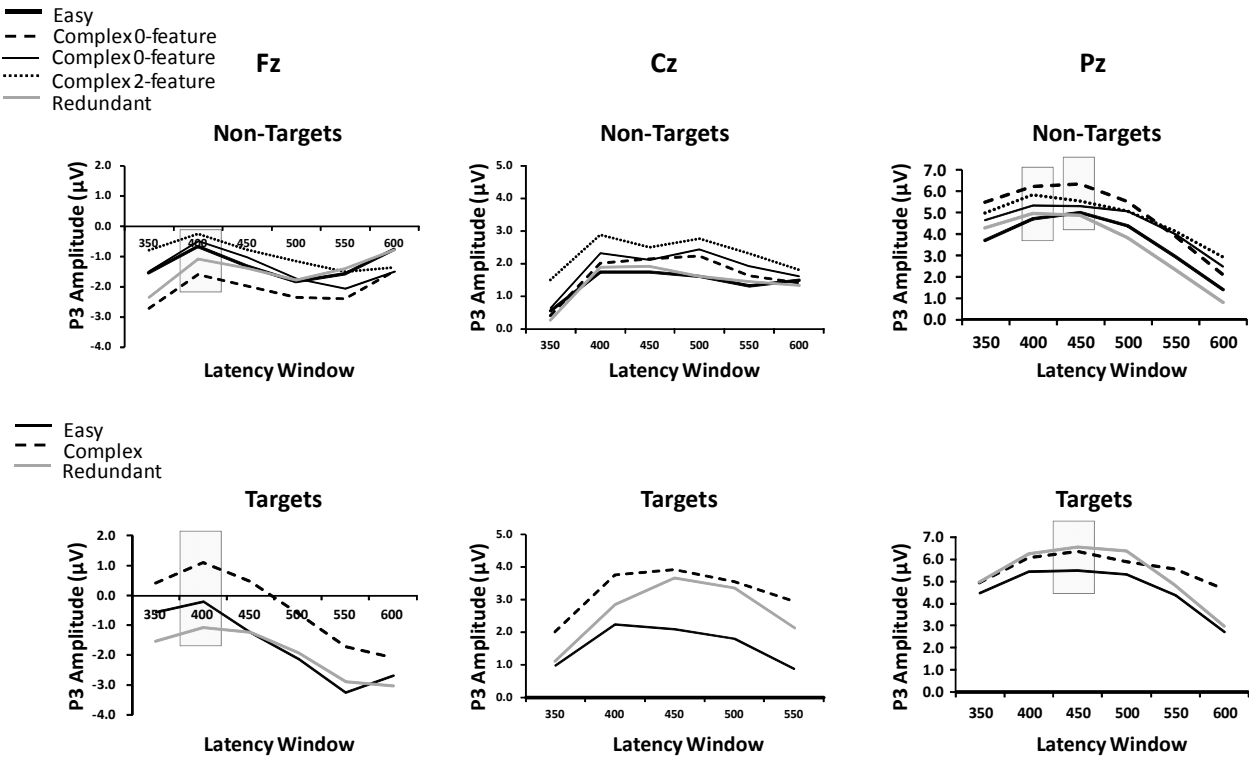


Figure 8: The mean amplitude at each of the 6 50-ms time windows used to assess the occurrence of the peak amplitude for the P3, at each of the three electrode sites Fz, Cz, and Pz. For these schematics, upward is positive. The scales are not meant to be the same at each electrode site, so that the timing of the largest amplitude could be emphasized at each site instead of the size of the mean amplitude for this particular figure. At Fz, the largest mean amplitude occurred in the second time window (350 – 400 ms) for all tasks and stimuli (highlighted by the grey box). There was some variability in the occurrence of the peak amplitude at Pz, dependent upon the stimulus. All targets had the peak amplitude occur in the third time window, between 400 and 450 ms. For the non-targets, most occurred earlier in the second time window of 350 – 400 ms, except the Easy non-target and the Complex 0-Feature non-target, which had their peak amplitude occur in the third time window, 400 – 450 ms.

Amplitude of the P3 at anterior and posterior electrode sites

The peak amplitude (peak mean amplitude, illustrated in Figure 9A at each of the three electrodes and as a difference score from Pz to Fz in Figure 9B) was then assessed as a function of task and stimulus complexity by first evaluating the relative size across the three different electrodes, the relative difference in size between electrode sites (the P3 gradient, Pz minus Fz), and then the size at the anterior and posterior electrodes separately.

The effect of task demands: When comparing the choice-based tasks across all electrode sites, the P3 amplitude was overall largest for the Complex task [main effect of task: $F(2,36) =$

6.73, $p = .003$, $\eta_p^2 = .27$] compared to both the Easy ($p = .03$) and Redundant ($p = .01$) tasks, which did not differ from each other. The P3 amplitudes for the target stimuli were larger than for the non-targets [$F(1,18) = 21.77$, $p < .001$, $\eta_p^2 = .55$]. There was a significant task x stimulus x electrode interaction [$F(4,72) = 4.02$, $p = .005$, $\eta_p^2 = .18$].

When comparing the relative size of the amplitude between the posterior and anterior sites (P3 gradient), as shown in Figure 9B the target stimulus had a smaller gradient compared to the non-target in the Complex task. The opposite pattern occurred for the Easy and Redundant tasks [task x stimulus interaction: $F(2,36) = 6.51$, $p = .004$, $\eta_p^2 = .27$].

At Fz only, there were again significant main effects of task [$F(2,36) = 5.27$, $p = .01$, $\eta_p^2 = .23$] and stimulus [$F(1,18) = 13.89$, $p = .002$, $\eta_p^2 = .44$]. The P3 amplitude was larger in the Complex task than in the Redundant task ($p = .04$), with an intermediate amplitude for the Easy task that did not significantly differ from either other task. On all tasks, the P3 amplitude was larger for target compared to the non-target stimuli ($p = .002$). At Pz the P3 amplitude did not differ as a function of task alone, but the 0-feature non-target and target stimuli in the Complex task were nearly the same compared to a larger amplitude for the target compared to non-target stimuli in the Redundant and Easy tasks [task x stimulus interaction: $F(2,36) = 4.04$, $p = .03$, $\eta_p^2 = .18$].

The effect of stimulus complexity: Similar results were found when the four stimuli of the Complex tasks were compared. The target stimulus had a larger P3 amplitude than all three non-targets [main effect of stimulus: $F(3,60) = 5.30$, $p = .003$, $\eta_p^2 = .21$; post hoc: target/0-feature, $p = .07$; target/1-feature, $p = .004$; target/2-feature, $p = .02$]. A significant stimulus x electrode interaction [$F(6,120) = 2.81$, $p = .01$, $\eta_p^2 = .12$] illustrated that the difference between stimuli was driven largely by what was happening at the anterior compared to posterior electrode sites. At Fz the P3 amplitude for the target stimuli was greater than for all of the other three stimuli [$F(3,60) = 6.10$, $p = .001$, $\eta_p^2 = .23$], including the 0-feature ($p = .028$), 1-feature ($p = .002$), and 2-feature ($p = .04$) non-targets. At Pz, the four stimuli did not differ from each other with respect to P3 amplitude. As seen in Figure 9B, for relative size of the amplitude for each stimulus between electrodes, the largest difference in gradient occurred between the 0-feature non-target and the target stimuli [main effect of stimulus [$F(3,60) = 3.59$, $p = .02$, $\eta_p^2 = .15$].

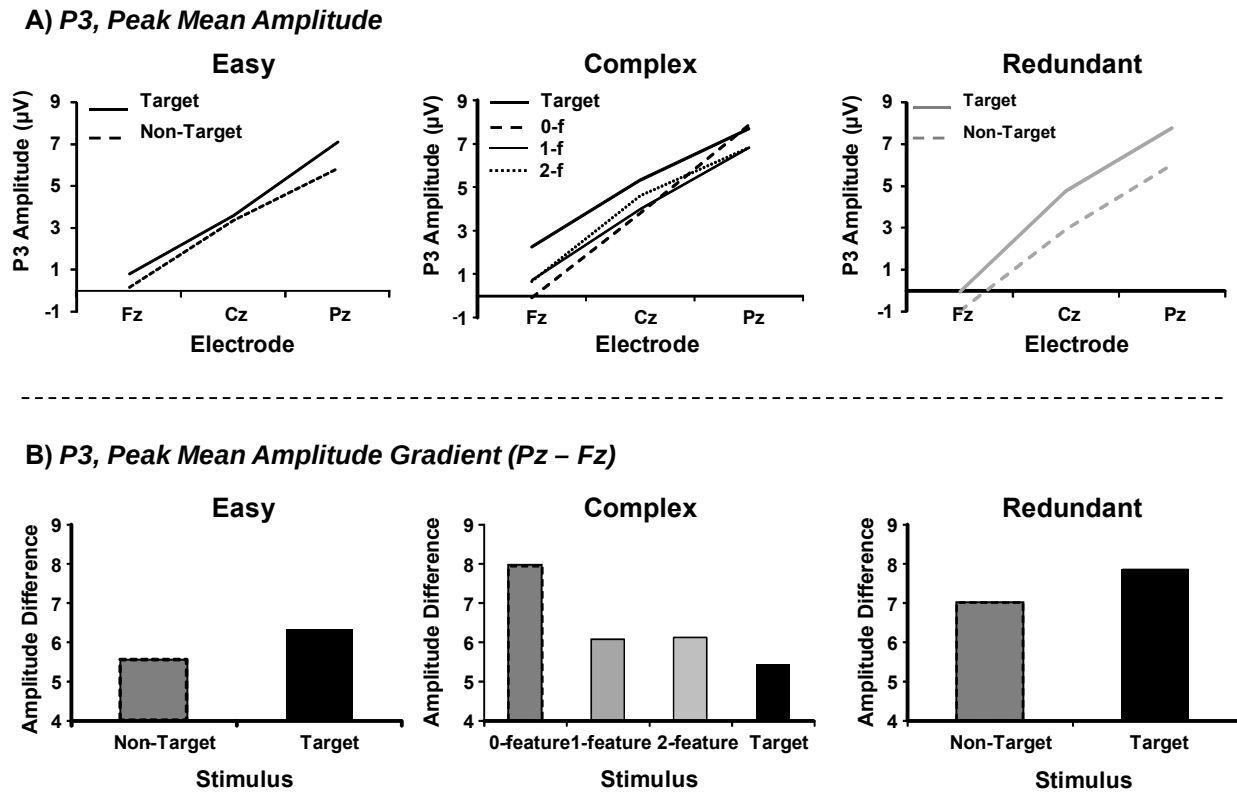


Figure 9: A) The peak mean amplitudes at each electrode site and for each stimulus. B) The peak mean amplitude gradient (Pz minus Fz) graphed per task and stimulus. For these schematics, upward is positive.

Summary of the P3: For all choice-based tasks and stimuli, as well as for the comparison of the stimuli within the Complex task alone, the peak latency occurred earlier at the more anterior Fz electrode compared to the posterior Pz electrode. There was some variability amongst stimuli with respect to the peak latency at Pz but not Fz, but the target stimuli generally had a longer latency than the non-target stimuli. For the mean amplitude, the largest amplitudes occurred at Pz and the smallest at Fz for all tasks and stimuli, the target stimuli generally had larger amplitudes than the non-target stimuli in all tasks, and the Complex task generated the largest overall amplitude compared to the Easy and Redundant tasks but this was largely driven by task differences at Fz but not Pz. The gradient measuring the size of the difference in amplitude from the Pz to the Fz electrodes depended upon task and stimulus type. The gradient was smaller for the target in the Complex task compared to the non-targets, whereas the opposite

pattern occurred for the Easy and Redundant tasks, and in the Complex task the gradient decreased in size sequentially from the 0-feature to 1-feature to 2-feature non-targets and then finally the target.

Source Distribution Modeling

The results from the statistical comparison of modeled source activity from each individual participant are presented in Figure 10. In the t-test comparing stimuli within the Easy task, there was greater activation in the left middle frontal gyrus for the target compared to the non-target at approximately 200 ms ($p < .001$). In the Complex task, the target showed greater activation compared to both the 1- and 2-feature non-targets in the right medial frontal gyrus at approximately 280 ms ($p = .014$ in the 1-feature comparison and $p = .007$ in the 2-feature comparison), and again later around the RT in the left parahippocampal gyrus ($p < .001$ in the 1-feature comparison and $p = .01$ in the 2-feature comparison). The non-targets showed greater source activity in some posterior regions compared to the target. The 0-feature non-target showed more early activation in the right superior temporal gyrus around 129 ms ($p = .001$) and both the 0-feature ($p < .001$) and 2-feature ($p < .001$) non-targets showed greater source activity just before their respective RTs in the left posterior cingulate. The Redundant target only showed more activity than the non-target post-response in the right insula ($p < .001$). In the comparison of the Easy and Redundant tasks, there were no differences in source activity to the target stimuli. The Easy task showed greater source activity in posterior regions, including the right parahippocampal area early around 136 ms ($p = .03$) and again later just before RT in the left posterior cingulate ($p < .001$). There was greater activation for the Redundant, compared to Easy, non-target early at approximately 228 ms in the left medial frontal gyrus ($p = .05$). In the correlation of source activity with RT, there was only a weak brain/behaviour correlation for the Redundant task ($p = .09$), representing a positive relationship between activity in the left medial frontal gyrus around 400 ms and RT for the Redundant non-target (the more neural activity, the slower the RT).

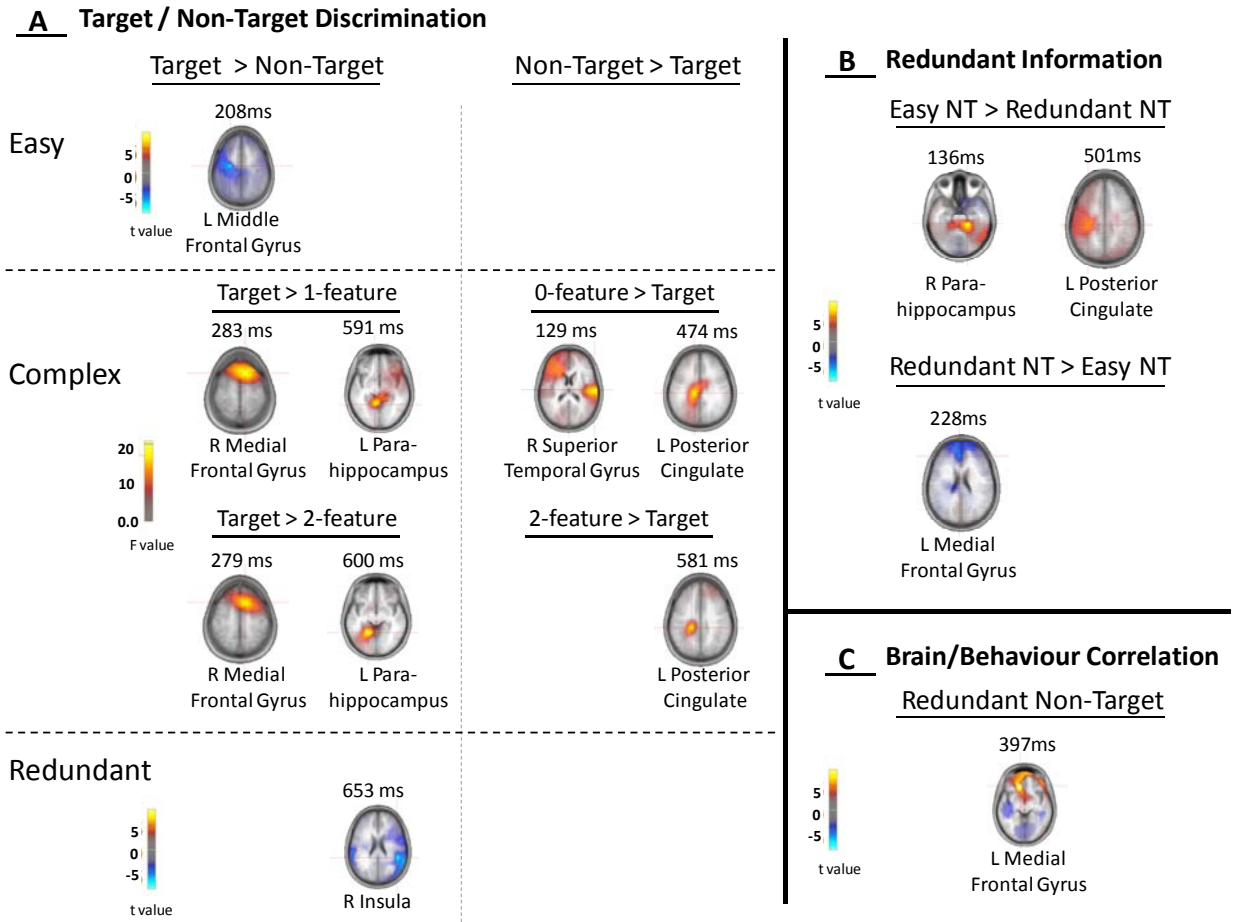


Figure 10: Statistical comparisons of peak activity distribution models calculated for each individual using Cortical Low resolution electromagnetic tomography Analysis Recursively Applied (CLARA, BESA, version 6.1). Note that the colour of the neural sources (red, blue) do not represent a particular direction of activity (i.e., target > non-target, for example), but are particular to the type of analysis (i.e., t-test vs. ANOVA), and also the order that variables were entered into an analysis. The colour is only meaningful for the brain/behaviour correlation in **Panel C**, where the red represents a positive correlation. **Panel A** shows comparisons between target and non-target stimuli for each of the three choice-based tasks (Easy, Complex, and Redundant) separately. In the t-test for the Easy task, there was greater activation in the left middle frontal gyrus for the target compared to the non-target early at approximately 200 ms ($p < .001$). In the ANOVA comparing all four stimuli in the Complex task, the target showed greater activation compared to both the 1- and 2-feature non-targets in the right medial frontal gyrus early at approximately 280 ms ($p = .014$ in the 1-feature comparison and $p = .007$ in the 2-feature comparison), and again later around response time in the left parahippocampal gyrus ($p < .001$ in the 1-feature comparison and $p = .01$ in the 2-feature comparison). The non-targets showed more activation in some posterior regions compared to the target. The 0-feature non-target showed more early activation in the right superior temporal gyrus around 129 ms ($p = .001$) and both the 0-feature ($p < .001$) and 2-feature ($p < .001$) non-targets showed greater activity before their respective response times in the left posterior cingulate. The Redundant target only showed more activity than the non-target post-response in the right insula ($p < .001$). **Panel B** shows the direct comparison of the Easy and Redundant non-target stimuli to test for the effect of redundant

information in the stimulus choice. (There were no differences in activation for a comparison of the target stimuli.) The Easy task showed greater activity in posterior regions, including the right parahippocampal area early around 136 ms ($p = .025$) and again later just before response time in the left posterior cingulate ($p < .001$). There was greater activation for the Redundant, compared to Easy, non-target early at approximately 228 ms in the left medial frontal gyrus ($p = .054$). **Panel C** shows the only significant brain/behaviour correlation, showing a positive relationship between activity in the left medial frontal gyrus around 400 ms and response time for the Redundant non-target (the more neural activity, the slower the response time).

Summary of source activity: In the Easy and Complex choice-based tasks, the target stimuli were correlated with a greater amount of activation in frontal regions compared to the non-target stimuli in frontal regions between 200 – 300 ms. The Complex task also showed more target-related activity around the response time in the parahippocampal gyrus. There was more posterior activity for the non-target stimuli compared to the target stimuli in the superior temporal gyrus and the posterior cingulate. Differences between stimuli in the Redundant task only appeared post-response in the insula. In the comparison of the Easy and Redundant tasks, the targets did not generate observable differential activity. However, the non-targets of the Easy task activated relatively more posterior activity, whereas the non-targets of the Redundant task activated relatively more medial frontal activity. Notably, the Redundant non-target was the only stimulus that showed a significant brain-behaviour correlation with response to RT, where a greater amount of frontal activity in the left medial frontal gyrus was associated with slower RTs.

4.4 Discussion

The purpose of this study was to characterize the neural correlates of increasing attentional demand using a visual task designed to sequentially introduce new attentional processes as a function of single stimulus characteristics and task instruction. Task demands influenced the latency and amplitude of the N1 and P3 waves, the anterior-posterior distribution of the P3 amplitude, and the patterns of modeled sources of peak neural activity. The results demonstrate new specificity with respect to the identification of attentional processes influenced by changes in task demands within a single task paradigm. This specificity can be useful for future research identifying the nature of subtle attentional problems in different clinical contexts.

4.4.1 The attentional processes represented by the N1

The modulations of latency and amplitude shown in this paradigm coincide with hypotheses of the N1 reflecting top-down gating of sensory information for the purpose of visually discriminating relevant information (Hopfinger & West, 2006; Luck et al., 1994). The inclusion of more stimulus information extended the overall N1 latency (Complex and Redundant > Easy). These relative N1 latency differences between tasks were not indicative of later RT (e.g., the Redundant task was similar to the Easy task behaviourally). This suggests that the basic time needed to process visual information represented by the N1 is not necessarily reflective of final RT. However, N1 latency was also modulated within each task dependent upon stimulus characteristics. Within the Easy and Redundant tasks the relative ease of stimulus differentiation elicited a longer target N1 latency compared to non-targets, whereas the N1 latencies were equivalent across stimuli types in the Complex task (where stimuli shared features).

The modulation of the N1 amplitude highlights the effect of task context more so than stimulus features on the gating of attention toward information for the discrimination of objects. N1 amplitude decreased from the first to the second repetition of the Simple RT task, possibly representing some habituation and a lesser amount of attention to this early stage of stimulus discrimination required during the second round. With respect to the overall N1 amplitudes evoked by each task, although N1 amplitude is usually larger in response to an increase in attention to the location or identity of a stimulus (Antonova et al., 2016; Hopfinger & West, 2006; Störmer, McDonald, & Hillyard, 2009; Whitford et al., 2011), the Easy task elicited the largest mean N1 amplitude. In comparison to the N1 amplitude of the first block of the Simple task, this suggests that the introduction of choice in the Easy task in response to the basic white shapes increased this early neural response. Given that the Complex and Redundant tasks contain more information, the reduction in N1 amplitude may suggest that the additional information requires more executive control and, perhaps especially in the case of the Redundant task, more suppression of potentially interfering information (Rorden, Guerrini, Swainson, Lazzeri, & Baylis, 2008). In contrast to the latency measures, the N1 amplitudes evoked by both the target and non-target stimuli within each of the Easy and Redundant tasks were nearly identical. However, in the Complex task where the stimulus features were the same as in the Redundant

task, there was a larger discrepancy between the N1 amplitudes as a function of stimulus type, with the target producing a larger N1 amplitude.

4.4.2 The attentional processes represented by the P3 latency and amplitude distributions

Generally, the P3 amplitude is considered to represent a multi-functional and multi-sourced set of processes that are primarily related to the evaluation of stimulus properties, the grouping of features to allow for target stimulus discrimination (Lithfous et al., 2016), and the inhibition of attention toward irrelevant information (Williams et al., 2016). The differences revealed here in P3 latency between the maximum amplitudes at the frontal (shorter latency) and parietal electrodes are in keeping with potentially different processing related to the anterior (P3a) compared to posterior (P3b) aspects of the P3 (Fjell & Walhovd, 2003; Wild-Wall, Falkstein, & Hohnsbein, 2008). With the caveat that interpretation of differential sources of activity based upon scalp location must be carried out with caution, the earlier processes represented by the anterior component are thought to be related to stimulus-driven orientation of attention while the later and more posterior component is more related to stimulus categorization and memory processes (Fjell & Walhovd, 2003; Wild-Wall et al., 2008). The lack of significant differences in P3 latency as a function of task suggests that, for these young participants, changes in task demands do not have a measurable effect on *when* these actions occur.

As with previous studies, the P3 amplitude was larger at parietal sites than frontal sites (Alperin, Mott, Holcomb, & Daffner, 2014; Davis et al., 2008; Fabiani, Friedman, & Cheng, 1998; Friedman et al., 1996, 1997; Reuter-Lorenz & Cappell, 2008; Reuter et al., 2013, 2016; Seidler et al., 2010). There was some amplitude modulation based upon stimulus characteristics and task context. Across all tasks the target stimuli produced the largest P3 amplitudes and the Complex task had larger P3 amplitudes compared to the Easy and Redundant tasks, although this was mostly driven by what was occurring at the Fz compared to the Pz electrode site. Although usually studied in the context of aging and the hypothesized compensatory recruitment of frontal attentional processes, this current study showed that a change in P3 amplitude distribution (Pz to Fz gradient) may index the recruitment of additional attentional processing needed to assess and respond to stimuli and task demands of differing complexities. This was especially evident in the Complex task where the gradient of the P3 amplitude for the target stimulus changed relative to

the non-targets (the target had the smallest gradient due largely to a larger P3 amplitude at the anterior site compared to the non-targets). In the context of this Complex task that had differing amounts of shared features between stimuli, the additional processes that are recruited to resolve the stimulus and response discriminations are measurable in young healthy adults.

The recruitment of additional processes related to anterior brain regions with increasing task demands was also supported by the source estimations that compared activity between the different stimulus types for each task. Very few differences were found between the categorization of a target and non-target stimulus, despite the relatively infrequent presentation of the target stimulus, in the tasks with lower demands (Easy and Redundant). The greater activity in the left middle frontal gyrus generated by the target stimulus in the Easy task may reflect a motor preparation potential that is generated with a change in movement of the right index finger (Pedersen et al., 1998) and the relatively low demands on other resources to categorize each simple stimulus (Godefroy & Rousseaux, 1996). By contrast, in the Complex task, the greater medial frontal involvement in target selection may represent a greater recruitment of anterior attentional resources to either energize the system to respond and/or resolve conflict, given the sensitivity of this region to these processes (Krawczyk, 2002; Stuss et al., 2002). The strength of the association between medial frontal activity and target selection was greater when comparing the target to the 2-feature than when comparing the target to the 1-feature non-target, suggesting that this area was more involved when the discrimination between stimuli was most difficult.

In the Easy task, the participants were able to rely mainly on the posterior resources needed to evaluate and compare the stimuli to memory representations in preparation for a response (Schmitt, Wolff, Ferdinand, & Kray, 2014), whereas in comparison the non-target stimulus in the Redundant task was weakly associated with greater activity in the left medial frontal lobe. For the Redundant task, this association with medial frontal activity may represent inhibitory or suppressive processes that were primarily engaged to allow the participants to focus attention on one feature for target selection and ignore the remaining features. This would also be in keeping with the larger P3 gradient (amplitude size at Pz minus Fz) in this task due in large part to the small amplitude size (which was actually a negative value for the non-target) at the Fz site. Previous research using a visual task with feature integration suggested that the processing of multiple stimulus features simultaneously was a separable but parallel process to the

processing of single features (Cortese, Bernstein, & Alain, 1999). The current results suggest that additional processes may possibly be occurring in conjunction with or possibly overriding (suppressing) feature integration processes. Given the presence of unnecessary information in the stimulus in the Redundant task, this P3 gradient and source data suggests that participants may have engaged inhibitory processes which could be sensitive to individual differences in performance. This may also account for the slight reduction in the Redundant N1 amplitude and the lengthening of the N1 latency compared to the Complex task, the lower P3 amplitude at Fz compared to the other tasks, and the negative correlation between the Redundant non-target RT and medial frontal source activity.

In sum, the administration of tasks with slightly changing demands in combination with EEG evoked measurable estimates of the different attentional processes beyond what can be captured in the analysis of the behavioural RT data alone. The changes in the N1 latency and amplitude as a function of task and stimulus properties captured the separable processes underlying the guidance of attention toward stimulus evaluation, including the control of either the enhancement or inhibition of stimulus features. The latency of the P3 amplitude measured at the anterior Fz site suggested that in young adults the timing of the maximization of processes thought to represent the orientation of attention to stimulus-based processing did not differ significantly as a function of stimulus properties or task instruction. By contrast, the timing of the subsequent stimulus categorization processes as represented by the latency of the P3 peak amplitude at the posterior Pz site differed by stimulus type (targets had a longer latency than non-targets) regardless of task context or instruction. Since the posterior P3 maximum amplitude occurs around the time of the response RT, the timing of these categorization processes likely are closest to the timing that is visible in outward response times. Task context did have a larger effect on P3 amplitude, mostly at the Fz compared to the Pz site due to the hypothesized recruitment of anterior (frontal lobe) attentional processes to respond to changing task demands. The Complex task, requiring the most effort to discriminate between stimuli, had the largest overall amplitude and showed a decreasing difference in amplitude between the anterior and posterior sites (i.e. a smaller gradient with more anterior process recruitment) as a stimulus became more similar to the target. The Redundant task, with its explicit instruction informing participants that there was unnecessary information contained within the stimuli, had the smallest

anterior P3 amplitude and largest gradient (with possible suppression of attention toward unnecessary information).

The goal of this study was to characterize the ERP markers of attentional processing elicited by a task designed to vary attentional requirements as a function of task context. The results confirmed that different attentional processes are measurable as a function of these task context changes. Additionally, this study provided evidence to support previous assumptions regarding some specificity of the nature of the primary processes elicited by each task (i.e., enhancement versus suppression of attention), as well as new information on potential differentiation of sources of different neural generators of activity. Increases in complexity relating to difficulty discriminating between stimuli for a binary choice relied increasingly on anterior attentional resources, especially for the identification of infrequent target stimuli. The presence of distracting information recruited anterior attentional resources to suppress unnecessary information, and this inhibitory ability was particularly sensitive to individual differences in performance. The importance of these findings lies in the modulation and measurement of multiple hypothesized attentional processes within one task paradigm. This potentially provides a means to more specifically measure general versus specific changes in attention in different types of clinically-relevant conditions. The N1 and P3 also provided easily-measurable indices of sensory functioning and the recruitment of frontal lobe processes, two areas thought to be especially important in neurodegenerative syndromes associated with aging.

Chapter 5

Hearing Loss in Older Adults Modulates Visual Sensory and Cognitive Event-Related Potentials

This chapter is a reformatted version of a manuscript in preparation for *Clinical Neurophysiology*.

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Abstract

This study examined the effects of mild hearing loss on visual attention in older adults. EEG recordings were collected while older participants with normal hearing for their age (ONHA) or mild hearing loss (OHL) completed a series of tasks with changing demands. The N1 and posterior to anterior scalp distribution of the P3 were selected to index endogenous attention during the evaluation of incoming stimulus information and attention to stimulus categorization and preparation for a response, respectively. These components were also selected to assess if performance represented a gain or loss in early visual functioning and to assess if more attentional processes are recruited in response to task complexity in the older adults with mild hearing loss. Compared to ONHA, the OHL group showed a general increase of the N1 latency and the anterior P3 latency. The OHL group's N1 latencies correlated with their performance on timed behavioral tests of speeded visual executive functioning. The ONHA group displayed a larger left than right hemisphere N1 amplitude compared to near-equivalent inter-hemispheric N1 amplitude for the OHL; this may reflect more processing efficiency by the ONHA group relating to a self-reported strategy of internally verbalizing the target stimulus during the task. The anterior P3 amplitude was reduced for the ONHA, but not the OHL group, when the task allowed for ignoring or suppressing unnecessary information. By contrast, the groups did not differ on the relatively later posterior P3 component. These data suggest that older adults with mild hearing loss differ from hearing-typical older adults in the timing and control of relatively early stage visual attentional processes. The similarity between the groups at the later P3 stage

suggests that not all aspects of cognitive functioning differ as a function of early stage hearing loss. The pattern of performance for the OHL group compared to the ONHA group on the N1 (slowing, inefficiency) and anterior P3 (no suppression) do not suggest that they are exhibiting compensatory visual processing, but further research is needed to determine if some serendipitous compensatory processing is occurring as a result of some decline in aspects of cognition.

5 Hearing loss in older adults modulates visual sensory and cognitive event-related potentials

5.1 Introduction

The third study combined the FIT tasks and EEG recordings of the N1 and P3 to examine the attentional response to increasing task demands in two groups of older adults differing in hearing thresholds. The main goal was to assess visual attention processes and whether changes in visual attention associated with hearing loss were specific to only certain visual attentional processes as captured by the FIT paradigm.

A previous report of the RT data from the FIT paradigm in these participants demonstrated a disruption in automatic response preparation in people with mild hearing loss compared to people with age-typical hearing where as more strategic processes remained intact, especially when there was more salient stimulus information available (Gillingham et al., 2018). This suggested that some, but not all, aspects of visual attention were affected by mild hearing loss.

The analysis of EEG data collected simultaneously with the administration of the FIT paradigm in younger adults demonstrated modulations of the N1 and P3 latencies and amplitudes that coincided with changes in the attentional processes of differing task demands. The N1 latency increased with the amount of stimulus information (i.e., the Complex and Redundant tasks had a longer latency than the Easy task), and the N1 amplitude decreased with increasing top-down control required to evaluate the stimulus (i.e., the Easy task had the largest N1 and the Redundant N1 was smaller than the Complex N1). Moreover, in addition to an expected general pattern of a larger P3 at posterior compared to anterior electrode sites, we observed changes in the anterior, more so than posterior, P3 amplitude when the task required enhancement or suppression of attention for stimulus discrimination (Fabiani et al., 1998; Reuter et al., 2016; Reuter et al., 2013). The anterior P3 increased in amplitude according to increasing demand both across tasks (i.e., Easy, Complex) and within task (i.e., the four stimuli in the Complex task). By contrast, smaller anterior P3 amplitudes for the Redundant task was interpreted to represent top-down control preventing the over-evaluation of features. These results provided sensitive

outcome metrics for the timing of the modulation of separable attentional processes that could be applied to the context of mild hearing loss in aging. The use of these outcome metrics allow for the assessment of the implication from the behavioural RT data that there was some specificity in the changes in visual attention that were associated with hearing loss (Gillingham, Vallesi, Pichora-Fuller, & Alain, 2018), and to assess if changes in different aspects of attention represented a reduction in visual cognition or an increase in visual efficiency or compensatory activity in older adults with, compared to without, mild hearing loss.

In this study the same EEG analysis strategy was applied to responses evoked while older adults with and without hearing loss performed the FIT tasks. The measurement of the N1 was chosen based upon previous research in middle-aged adults with hearing loss that showed an increase in visual processing efficiency indexed by a decrease in N1 latency and an increase in N1 amplitude compared to age-matched peers with normal hearing (Campbell & Sharma, 2014). In the analysis of the behavioural RT on the FIT task (Gillingham et al., 2018), the older adults with mild hearing loss did show some general slowing as well as difficulty with the more automatic aspects of response preparation. Therefore, it could be expected that the early visual processes that are not under full strategic control may be affected in these same adults. However, as shown in the analysis of the EEG data in younger adults, the N1 activity is somewhat separable from, and not necessarily reflective of, the final RT outcome. Therefore, it is also possible that older adults with mild hearing loss may show an increase in efficiency of early visual processing as shown by middle-aged adults with mild-hearing loss (Campbell & Sharma, 2014). The measurement of the P3 was chosen to capture separate processes in higher-order attention, including the recruitment of hypothesized anterior (frontal) processes in aging. Evidence from previous studies suggests that certain ‘aging’ effects on cognition may be exaggerated due to the unintentional inclusion of participants with hearing loss (Guerreiro & Van Gerven, 2017), but also that middle-aged adults with mild hearing loss recruit more frontal brain regions than age-matched peers without hearing loss for hypothesized compensatory processing during listening tasks (Campbell & Sharma, 2014). Therefore, the finding of greater recruitment of frontal regions in aging (Cabeza et al., 2002; DiGirolamo et al., 2001) may also be tainted with a mixture of participants with and without obvious clinical conditions such as hearing loss in aging that may promote the engagement of extra processing. If older adults with hearing loss compared to their age-matched peers also recruit more frontal regions to complete visual

attention tasks, then the amplitude of the anterior P3 is expected to be higher and the relative distribution gradient from the posterior to anterior electrode sites flatter for this group with mild hearing loss whereas the older adults with age-normal hearing may show varying recruitment of frontal processes dependent upon task context.

5.2 Methods

5.2.1 Participants

The two groups of older participants described in Chapter 2 were involved in this study: 17 older adults with typical hearing thresholds for their age (ONHA) and 15 older adults with mild hearing threshold elevations (OHL).

5.2.2 Measures

Standard neuropsychological measures

A brief battery of standardized neuropsychological tests was administered to all participants to evaluate the main cognitive processing thought to be utilized by the experimental tasks. The tests provided an index of functioning within cognitive domains, namely: processing speed (Trail Making Test A, Reitan & Wolfson, 1985; Stroop Word Reading, Stroop, 1935; Digit Symbol Coding, Wechsler, 1997a), visual (Spatial Span Forward, Wechsler, 1997b) and auditory (Digit Span Forward, Wechsler, 1997b) attention, visual (Spatial Span Backward, Wechsler, 1997b) and auditory (Digit Span Backward, Wechsler, 1997b) working memory, speeded visual executive functioning (Trail Making Test B, Reitan & Wolfson, 1985; Stroop Colour Naming, Stroop Interference, Stroop, 1935), other executive functioning (Phonemic, Newcombe, 1969, and Semantic, Benton, 1968, Fluency; CVLT-II interference Trial B, Delis et al., 2000), Visual Memory (Digit Symbol Incidental Learning, Wechsler, 1997a), and verbal memory (CVLT-II Total Recall on 5 Learning Trials, Short-Delay Free Recall, Long Delay Free Recall, Delis et al., 2000).

Experimental task

The FIT task was administered to all participants as outlined in the general methods in Chapter 2.

5.2.3 Procedure

The procedure for task administration and the collection and processing the EEG data was as described in the general methods in Chapter 2.

5.2.4 Data analysis

N1 – The interaction between attention and visual sensory information

The effects of stimulus type and task on the N1 were quantified at posterior electrode sites over the left (P5, P7, P07) and right (P6, P8, P08) hemispheres. The window to capture the peak latency was selected as 130 – 230 ms following stimulus presentation, and the mean amplitude was calculated as +/- 40 ms surrounding the extracted peak latency.

The first set of analyses examined the influence of changing task demands on visual discrimination as indexed by the peak latency and mean amplitude of the N1. Changes in simple baseline responding were evaluated by comparing the two blocks of the Simple RT task in a 2 (task) x 2 (hemisphere) x 3 (electrode) x 2 (group) mixed ANOVA. The effect of task demands on amplitude and latency was assessed using a 3 (task: Easy, Complex, Redundant) x 2 (stimulus: non-target, target), x 2 (hemisphere) x 3 (electrode) x 2 (group) mixed ANOVA. Only the 0-feature non-target and target stimuli were included for the Complex task as these stimuli offered the most equivalent comparison to the stimuli found in the Easy and Redundant tasks. The effect of stimulus complexity was assessed in the Complex task only using a 4 (stimulus) x 2 (hemisphere) x 3 (electrode) x 2 (group) mixed ANOVA.

P3 – Stimulus evaluation and categorization

Following previous research on the assessment of the distribution of the P3, this deflection was measured at midline central electrode sites Pz, Cz, and Fz for each stimulus within each of the choice-based tasks (Reuter et al., 2016). Given the wide latency range of the

P3 and the possibility of inter-individual and inter-task variability, mean amplitudes were calculated for 8 time windows of 50 ms each from 300 ms to 700 ms after stimulus onset so that peak latency could be more accurately traced over time. The amplitude was then extracted from the time window where it was largest (labeled the peak mean amplitude, Reuter et al., 2016) for each task, stimulus, and participant.

For the P3 wave, the latency of the peak amplitude was first evaluated for an interaction between the time window and electrode site (i.e., does the latency of the peak amplitude differ between electrode sites) by comparing the eight time windows across electrodes in a 3 (task: Easy, Complex, Redundant) x 2 (stimulus) x 8 (time window) x 3 (electrode) x 2 (group) mixed ANOVA. Only the 0-feature non-target and target stimuli were included for the Complex task. To assess for the influence of within task stimulus complexity, the peak latency was assessed in just the Complex task using a 4 (stimulus) x 8 (time window) x 3 (electrode) x 2 (group) mixed ANOVA. These analyses revealed interactions of the time window and electrode variables with the task, stimulus, and group variables. Follow-up analyses then examined the peak latency separately for each task in a 2 (stimulus) x 8 (time window) x 2 (group) mixed ANOVA at each of the three electrode sites.

The P3 amplitude was first assessed for the effect of task demands by comparing the three binary choice tasks in a 3 (task) x 2 (stimulus) x 3 (electrode) x 2 (group) mixed ANOVA, followed by a 4 (stimulus) x 3 (electrode) x 2 (group) mixed ANOVA for just the Complex task to assess for the effect of task complexity. The change in the distribution of the amplitude with a focus on the posterior to anterior sites was assessed via the P3 gradient (Pz – Fz) in a 3 (task) x 2 (stimulus) x 2 (group) mixed ANOVA. Follow-up analyses at the Pz and Fz electrode sites separately allowed for the examination of interaction effects, as well as confirmation of how amplitude differences between stimuli and tasks may be contributing to differences in the analyses across electrode sites given the required caution for interpretations of findings involving different electrode locations in ERP research (Keil et al., 2014).

Neuropsychological measures and correlations with standard measures of speeded attention

The comparisons of the groups on scores for some of the individual neuropsychological tests were reported previously (Gillingham et al., 2018, Chapter 3). No participants showed impairments on the standard measures and there were no statistical differences in group

performance on the previously reported tests or on any of the additional tests that are included in this study, confirming our selection of participants who were not measurably impaired based upon standard measures of cognition. Spearman correlations were used to assess the relationship between ERP measures (the N1 latency, the N1 amplitude, the peak mean amplitude gradient defined by the difference between the peak mean amplitude at the Pz and Fz electrodes) and indices of attention under speeded conditions as assessed by the standard neuropsychological tests (processing speed and speeded visual executive functioning). These cognitive domains were chosen because they represent standardized measures of the multiple speeded attentional processes that are incorporated within the FIT task. For these analyses, the neuropsychological scores were converted into z-scores based upon normative data, and then the tests representing each of the cognitive domains were combined to create an index score for that domain. The z-scores for the timed measures were reversed so that a higher z-score represented better functioning (faster speed rather than slower speed). For the N1, the latencies and amplitudes used in the correlation were averaged across the three electrodes for each hemisphere separately.

5.3 Results

5.3.1 ERP results

N1 – The Interaction between attention and sensory (visual) information

Figure 11 shows the N1 modulation for each task.

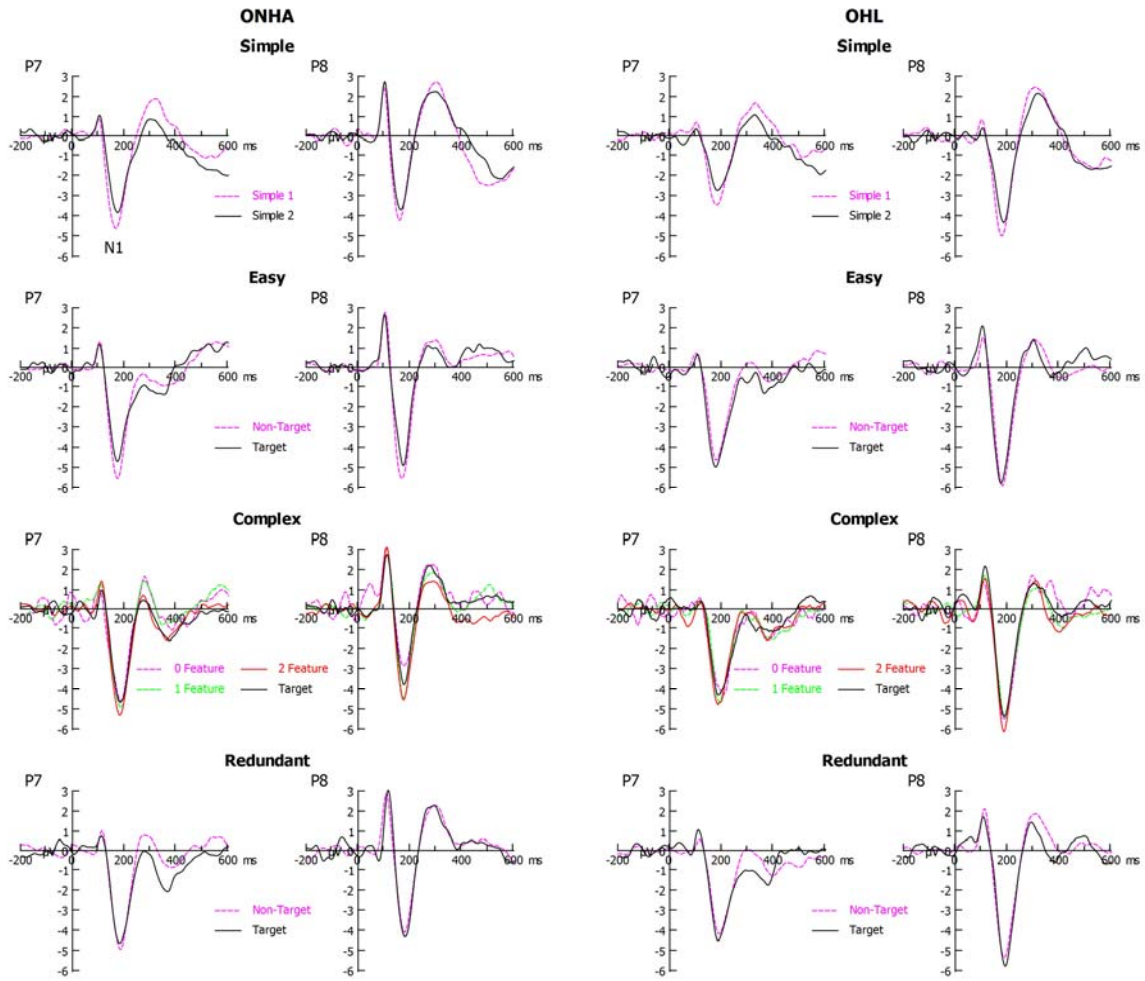


Figure 11: The grand averaged ERP wave form for the N1 for each group, task, and stimulus measured from posterior electrode sites, using electrodes P7 and P8 as an illustrative example. ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

N1 Latency

The change in baseline responding over task repetitions: Comparing peak latency across repetitions of the Simple RT tasks, the OHL group had an overall longer N1 latency than the ONHA group [$F(1,30) = 7.62, p = .01, \eta_p^2 = .20$]. The N1 latency was longer in the left compared to the right hemisphere across both tasks for both groups [$F(1,30) = 4.76, p = .04, \eta_p^2 = .20$].

The effect of task demands: Comparing the three binary choice tasks, the peak N1 latency was slower for the OHL group by about 9 ms compared to the ONHA group across all tasks, although the difference did not reach significance [$p = .098$]. The Easy task had a shorter N1

latency compared to both the Complex and Redundant tasks for both groups [main effect of task: $F(2,58) = 32.65, p < .001, \eta_p^2 = .53$]. The overall N1 latency was again longer in the left compared to the right hemisphere for both groups [main effect of hemisphere: $F(1,29) = 4.71, p = .04, \eta_p^2 = .14$].

The effect of stimulus complexity: Within the Complex task, the N1 latency in the OHL group was on average 10 ms later than the ONHA group [$F(1,30) = 4.51, p = .04, \eta_p^2 = .13$]. The overall N1 latency was longer in the left compared to the right hemisphere for both groups [$F(1,30) = 7.92, p = .009, \eta_p^2 = .21$].

N1 Amplitude

The change in baseline responding over task repetitions: In the comparison of the two blocks of Simple RT, the N1 mean amplitude was larger in the first compared to the second block in both groups [$F(1,30) = 12.84, p = .001, \eta_p^2 = .30$]. The N1 amplitude was larger in the left compared to the right hemisphere for the ONHA group whereas the N1 amplitude was either larger in the right hemisphere or the two hemispheres were nearly the same for the OHL group [hemisphere x group interaction: $F(1,30) = 5.02, p = .03, \eta_p^2 = .14$].

The effect of task demands: The three choice-based tasks differed in their evoked N1 amplitude size for both groups [main effect of task: $F(2,58) = 3.51, p = .04, \eta_p^2 = .11$], the Easy task having a significantly larger amplitude than the Complex task ($p = .08$). The amplitude was larger in the left compared to the right hemisphere for the ONHA group, whereas the N1 amplitude was either larger in the right hemisphere or the two hemispheres were nearly the same for the OHL group [hemisphere x group interaction: $F(1,29) = 5.14, p = .03, \eta_p^2 = .15$].

The effect of stimulus complexity: Within the Complex task, the N1 amplitude was larger for the 2-feature non-target stimuli in comparison to both the 0-feature non-target ($p = .03$) and the target ($p = .01$) stimuli [main effect of stimulus type: $F(3,90) = 4.49, p = .006, \eta_p^2 = .30$]. The amplitude was larger in the left compared to the right hemisphere for the ONHA group, whereas the N1 amplitude was either larger in the right hemisphere or the two hemispheres were nearly the same for the OHL group [hemisphere x group interaction: $F(1,30) = 8.53, p = .007, \eta_p^2 = .22$].

Summary of the N1: The OHL group had a longer N1 latency than the ONHA group on all tasks, but the difference between the groups was only statistically significant on the Simple RT tasks and the Complex task. For both groups, the N1 latency was shorter for the Easy task compared to the Complex and Redundant tasks, and also longer in the left compared to the right hemisphere. For N1 amplitude, the two groups were similar in that the amplitude was larger in the first compared to second block of the Simple RT task and was larger in the Easy task compared to the Complex task which had the smaller amplitude of the three choice-based tasks. The only group differences occurred in the hemispheric asymmetry of amplitude size. For the ONHA group, the amplitude was larger in the left compared to right hemisphere for all tasks, whereas the opposite pattern occurred for the OHL group although the ONHA group actually had a larger difference between hemispheres than the OHL group.

P3 – Stimulus evaluation and categorization

Figure 12 shows the grand averaged P3 waveforms at Fz, Cz, and Pz for each task. See Figure 13 for an illustration of the latency time windows analyzed for the P3 at the Fz and Pz sites.

Latency of the peak amplitude of the P3 at anterior and posterior electrode sites

The latency was assessed by identifying the 50-ms time window in which the peak amplitude occurred. The interaction terms of this time window variable with the electrode variable assessed differences in latency at anterior and posterior electrode sites. The interaction terms with the task, stimulus, and group variables were additionally examined for the effects of task demands, stimulus type, and group membership.

The effect of task demands: In the analysis of the latency of the peak P3 amplitude across the three binary choice tasks, there was a significant time window x electrode interaction [$F(14,406) = 12.64, p < .001, \eta_p^2 = .30$]. Overall, as shown in Figure 13, the latency of the peak occurred earlier, in the 350 – 400 ms time window, at the Fz electrode site compared to the Pz electrode where the peak occurred within the 450 – 500 ms time window. There was a significant stimulus x time window x electrode x group interaction [$F(14,406) = 2.86, p < .001, \eta_p^2 = .09$], and the task x stimulus x time window x electrode x group interaction was on the threshold of

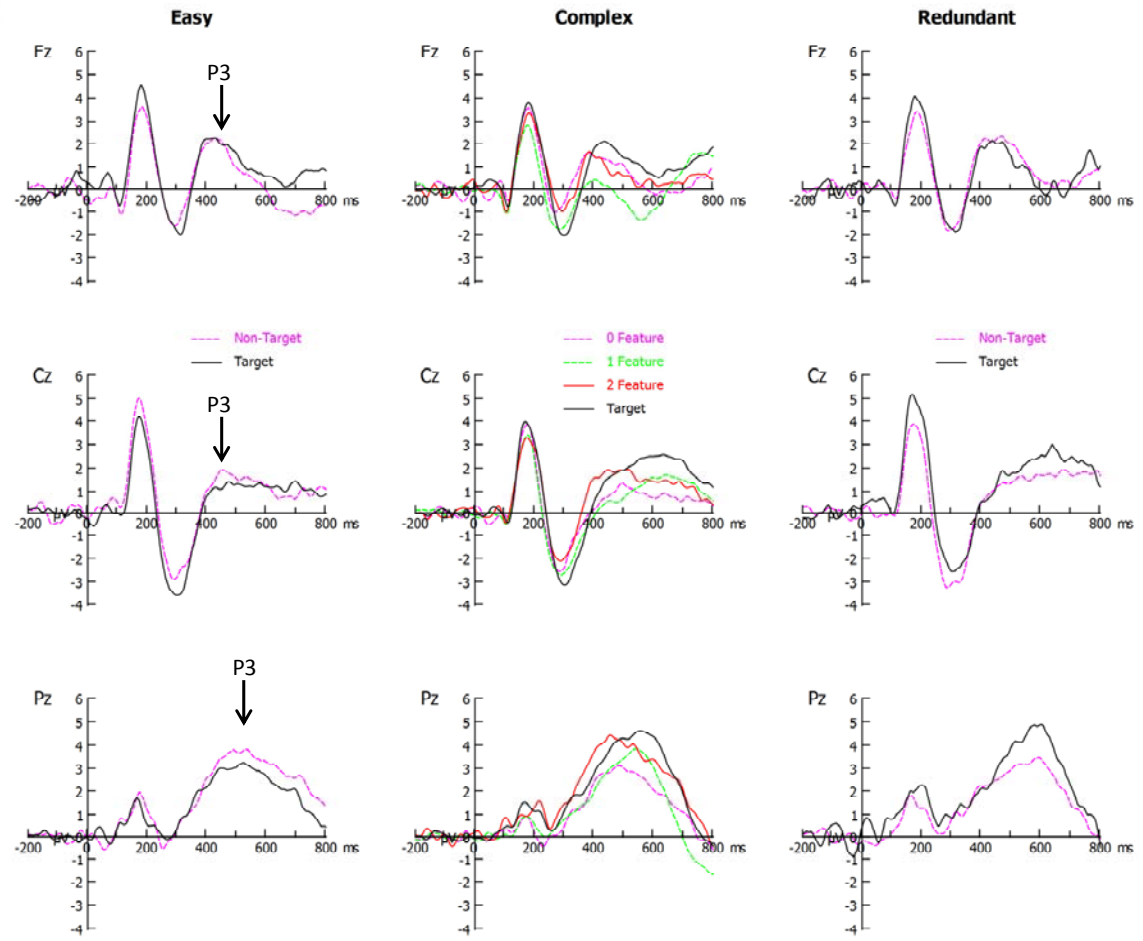
significance [$F(28,812) = 1.49, p = .051, \eta_p^2 = .05$]. Follow-up ANOVAs compared the latency across the three tasks at the Pz and Fz electrodes separately.

At Pz, the peak P3 amplitude in the Complex task occurred across later time windows (500 – 600 ms) than the Easy and Redundant tasks (450 – 550 ms). This later peak amplitude within the Complex task was largely driven by the OHL group as can be seen in Figure 13, although there were no statistically significant differences between the groups [task x time window interaction: $F(14,406) = 2.94, p < .001, \eta_p^2 = .09$]. The peak latency occurred later for non-target (500 – 550 ms) compared to the target (450 – 500 ms) stimuli in all tasks and for both groups [stimulus x window interaction: $F(7,203) = 9.10, p < .001, \eta_p^2 = .24$].

At Fz, the P3 peak again occurred later for the Complex task (450 – 500 ms) than the Easy and Redundant tasks (350 – 400 ms) for both groups [task x time window interaction: $F(14,406) = 6.38, p < .001, \eta_p^2 = .18$]. The ONHA group had a later peak for the Complex target and 0-feature non-target (400 – 450 ms) compared to all other stimuli (350 – 400 ms), whereas the OHL group had a relatively later peak for most stimuli (Complex target and all non-targets, 400 – 450 ms) with the exception of the Easy and Redundant targets (350 – 400 ms) [stimulus x time window x group interaction: $F(7,203) = 2.62, p = .013, \eta_p^2 = .08$].

The effect of stimulus complexity: In the analysis of the four stimuli in the Complex task alone across the three electrodes, there was a significant stimulus x window x task interaction [$F(42,1260) = 3.30, p < .001, \eta_p^2 = .10$]. At Pz only, the amplitude of the non-target stimuli generally had a peak that occurred later (500 – 600 ms) than the peak for the target stimulus (450 – 550 ms) for both groups [stimulus x time window interaction: $F(21, 630) = 3.63, p < .001, \eta_p^2 = .11$]. There were no significant effects at Fz.

ONHA



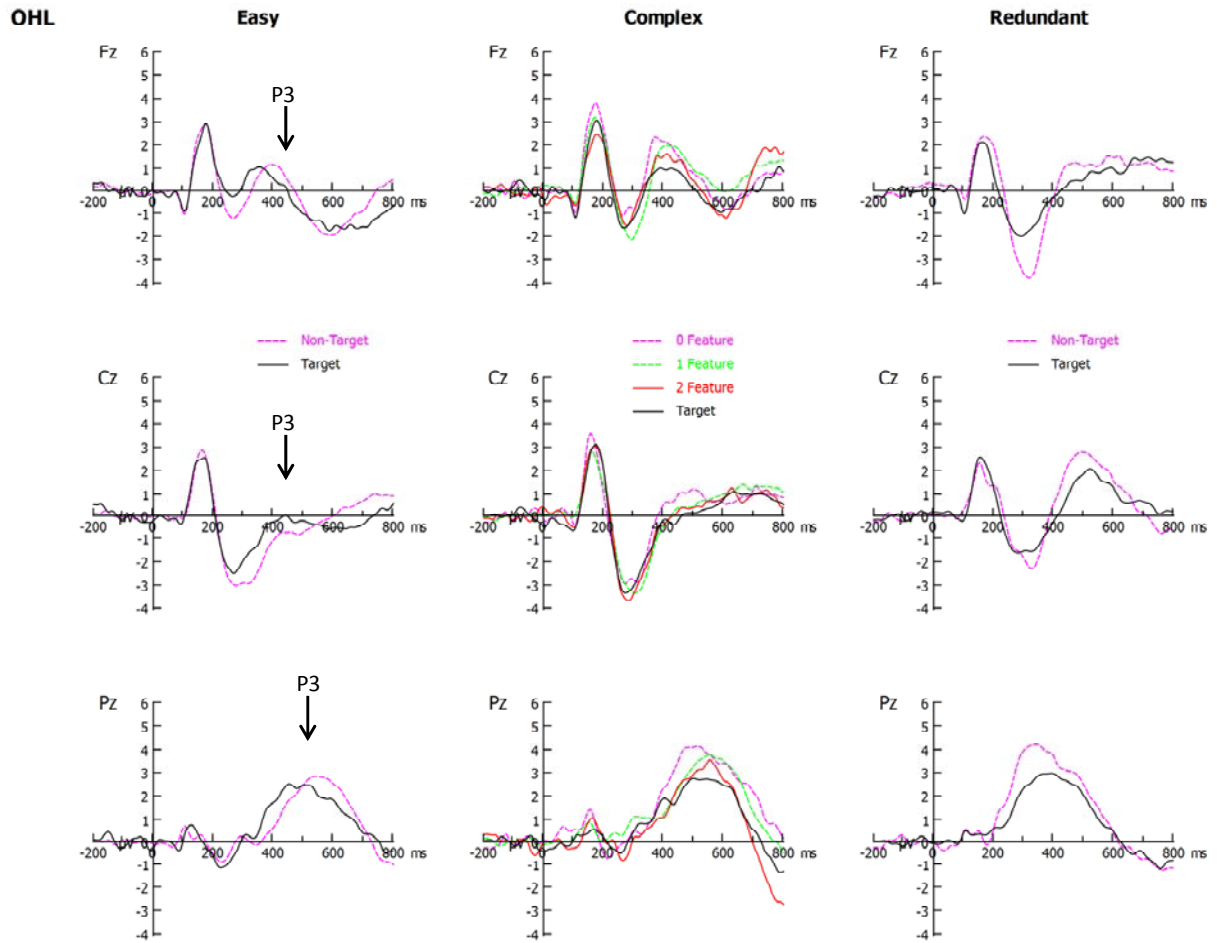


Figure 12: The grand averaged ERP waveform for the P3 at electrode Fz, Cz, and Pz for each task and stimulus for the ONHA group and the OHL group. ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

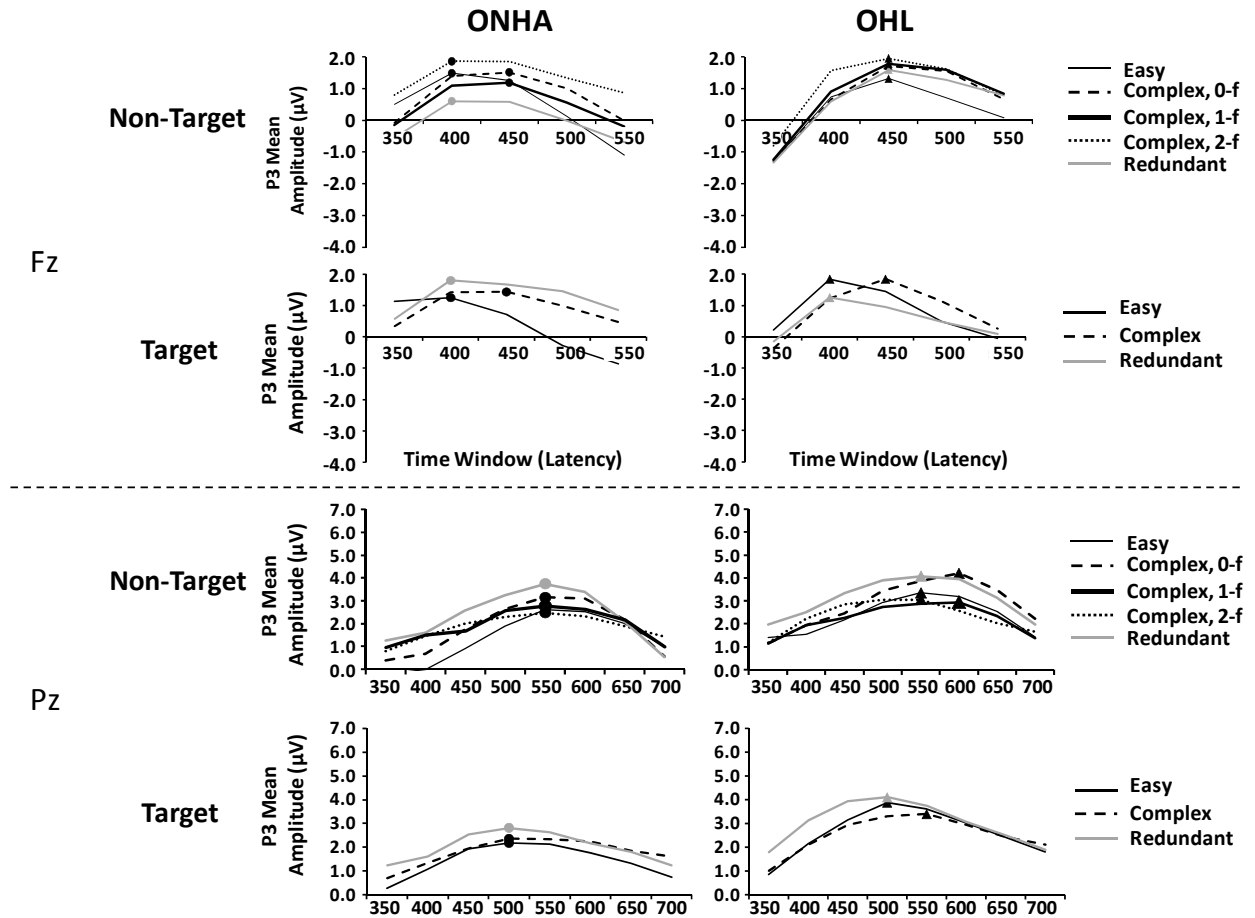


Figure 13: The mean amplitude at each of the 8 50-ms time windows used to assess the occurrence of the peak mean amplitude for the P3 at Fz and Pz electrode sites. The scales are not meant to be the same at each electrode site, so that the timing of the largest amplitude could be emphasized at each site instead of the size of the mean amplitude for this particular figure. At the posterior Pz site, differences between the groups in latency are not statistically different. Non-target stimuli generally peaked later than the target for all groups. The two groups did differ at the Fz site. The ONHA group had similar latencies to the Young group as shown in the previous study, with peak amplitudes occurring between 350 – 400 ms, with the exception of the target and two of the non-targets in the Complex task. The OHL group had the peak mean amplitude occur for the Easy and Redundant targets between 350 – 400 ms, but all other stimuli occurred later between 400 – 450 ms. ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

Amplitude of the P3 at anterior and posterior electrode sites

Figure 14 illustrates the peak mean amplitudes at each of the three electrode sites.

The effect of task demands: P3 amplitude differed as a function of electrode site for both groups [main effect of electrode: $F(2,58) = 12.72, p < .001, \eta_p^2 = .31$], where the amplitude at Pz

was larger than the amplitude at both Fz ($p = .001$) and Cz ($p < .001$). The P3 amplitude was significantly smaller in the Easy than the Redundant task ($p = .005$), and the Complex task evoked an intermediate amplitude [main effect of task: $F(2,58) = 3.24$, $p = .05$, $\eta_p^2 = .10$]. The change in P3 amplitude from Pz to Fz (P3 gradient) differed as a function of task, stimulus, and group membership [task x stimulus x group interaction: $F(2,58) = 3.18$, $p = .05$, $\eta_p^2 = .10$]. Comparisons of the amplitudes across tasks were carried out at the Fz and Pz sites separately. There were no significant differences in P3 amplitude at Pz as a function of task, stimulus, or group membership. At Fz, as can be seen in Figure 15, for the ONHA group the amplitude for the non-target in the Redundant task is much smaller than the amplitude for the target, whereas the amplitudes for the two stimuli do not differ as much for the OHL group [task x stimulus x group interaction: $F(2,58) = 4.977$, $p = .01$, $\eta_p^2 = .15$].

The effect of stimulus complexity: When the four stimuli in the Complex task were assessed, the P3 amplitude at Pz was larger than the amplitude at both Fz ($p = .007$) and Cz ($p < .001$) for both groups [main effect of electrode: $F(2,60) = 9.23$, $p < .001$, $\eta_p^2 = .24$]. There were no differences in the P3 gradient amongst the four stimuli in the Complex task when it was examined on its own.

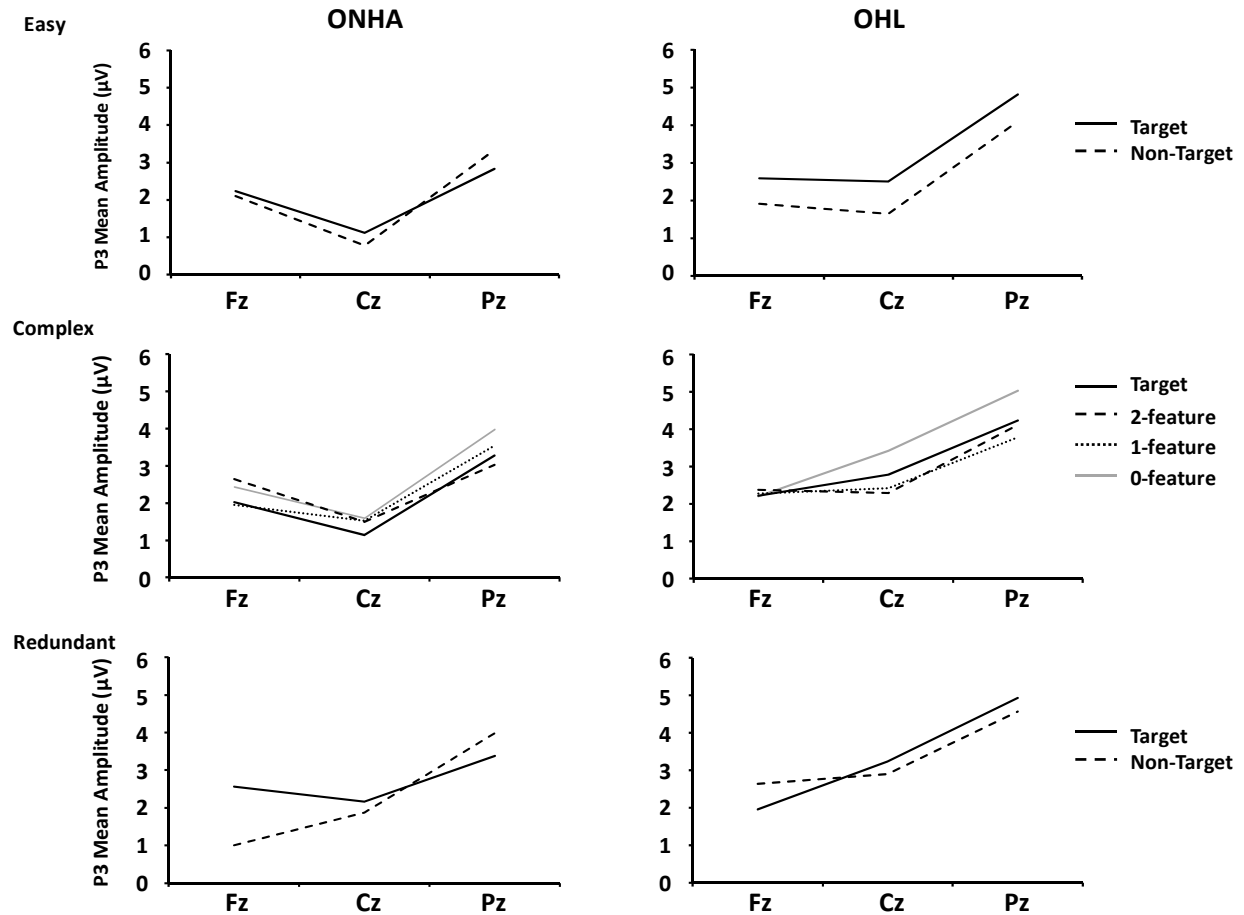


Figure 14: The peak mean amplitudes at each electrode site and for each stimulus in the three choice tasks. Both older groups show the expected larger amplitude at the Pz site compared to the Fz site. The amplitudes at Fz differ between groups in one respect. The ONHA group shows a reduction in amplitude for the Redundant non-target, whereas the OHL group does not. ONHA, older adults with typical hearing for their age; OHL, older adults with mild hearing loss.

Summary of the P3: The latency of the P3 peak generally occurred earlier at Fz than Pz. However, there was some variability in latency as a function of task, stimulus, electrode, and group membership. For both groups, the P3 latency of the non-target stimuli occurred later than the target stimuli for all tasks at Pz. The OHL group demonstrated later peak latencies for the Complex stimuli but they did not significantly differ from the ONHA group. At Fz, however, while peak P3 latencies for the Complex stimuli occurred later when compared to those in the other tasks for both groups, the OHL group demonstrated later latencies for all non-target stimuli compared to the ONHA group. The P3 amplitude at Pz was larger than the amplitude at Fz and

Cz in all analyses for both groups. The amplitude gradient from Pz to Fz was not the same for both groups. The groups were similar in the P3 amplitude gradient in the most difficult (Complex) task, but differed in the task that allowed for inhibition of unnecessary information (Redundant). Follow-up analyses at each electrode site showed that there were no group differences in amplitude at Pz. However, at Fz the ONHA group showed a reduced P3 amplitude for the non-target stimuli in the Redundant task whereas the OHL group did not.

5.3.2 Correlations between ERP values and cognitive indices

The correlation results indicating significant associations between indices of processing speed and speeded visual executive functioning and the N1 latency are presented in Table 1. A higher z-score represented better performance within each domain. For the ONHA group, only a couple of significant correlations occurred involving the index for speeded visual executive functioning. By contrast, speeded visual executive functioning was negatively correlated with all tasks and stimuli for the OHL group.

In the correlations between N1 amplitude and the indices of cognitive function (significant results presented in Table 2), there were no significant correlations between processing speed or speeded visual executive functioning and N1 amplitude for the ONHA group. For the OHL group, N1 amplitude for the first Simple task and most stimuli in the Complex task correlated with the speeded visual executive functioning index.

For the P3 gradient, the results are presented in text instead of a table because only the processing speed index showed a negative correlation with the P3 gradient for the target stimulus in the Redundant task ($r = -.485, p = .048$) for the ONHA group. There were no correlations between these speeded indices of cognitive function and P3 gradient for the OHL group.

Summary for the correlations between ERP measures and cognition: The N1 latency correlated negatively with indices of cognitive function, especially for the index of speeded visual executive functioning for the OHL group. The N1 amplitude for most stimuli in the Complex task again correlated negatively with speeded visual executive functioning for the OHL group (higher amplitude, worse speeded visual executive functioning). The P3 amplitude gradient was only negatively correlated with processing speed for the Redundant target for the ONHA group.

Table 1: Significant results of Spearman correlations between the N1 latency and indices of cognitive functioning. *l*, left hemisphere; *r*, right hemisphere. T, target; NT, non-target. * denotes a p-value between .01 and .05, and ** denotes a p-value less than .01.

Latency	Simple 1	Simple 2	Easy		0-F	Complex		T	Redundant	
			NT	T		1-F	2-F		NT	T
<i>ONHA</i> Processing Speed Speeded Visual Executive Functioning	<i>r</i> : $r = -.54^*$								<i>l</i> : $r = -.59^*$	
<i>OHL</i> Processing Speed Speeded Visual Executive Functioning	<i>l</i> : $r = -.73^{**}$	<i>l</i> : $r = -.60^*$ <i>l</i> : $r = -.68^{**}$	<i>l</i> : $r = -.73^{**}$ <i>l</i> : $r = -.76^{**}$ <i>r</i> : $r = -.51^*$	<i>l</i> : $r = -.69^{**}$ <i>l</i> : $r = -.75^{**}$ <i>r</i> : $r = -.53^*$	<i>l</i> : $r = -.64^*$ <i>l</i> : $r = -.5^*$ <i>r</i> : $r = -.65^{**}$	<i>l</i> : $r = -.56^*$	<i>l</i> : $r = -.52^*$ <i>r</i> : $r = -.5^*$	<i>l</i> : $r = -.52^*$	<i>l</i> : $r = -.69^{**}$	<i>l</i> : $r = -.71^{**}$ <i>r</i> : $r = -.80^{**}$

Table 2: Significant results of Spearman correlations between the N1 amplitude and indices of cognitive functioning. *l*, left hemisphere; *r*, right hemisphere. T, target; NT, non-target. * denotes a p-value between .01 and .05, and ** denotes a p-value less than .01.

Amplitude	Simple 1	Simple 2	Easy		0-F	Complex		T	Redundant	
			NT	T		1-F	2-F		NT	T
<i>ONHA</i> Processing Speed Speeded Visual Executive Functioning										
<i>OHL</i> Processing Speed Speeded Visual Executive Functioning	<i>r</i> : $r = -.55^*$				<i>l</i> : $r = -.59^*$ <i>r</i> : $r = -.61^*$		<i>l</i> : $r = -.57^*$	<i>l</i> : $r = -.62^*$		

5.4 Discussion

The purpose of this study was to examine visual processing in two groups of older adults who differed in audiometric thresholds. In addition to the pure-tone hearing thresholds that were used to categorize the two groups of participants, the older adults with mild hearing loss (OHL) had reduced ability to hear speech in multi-talker babble. They also reported difficulties with practical, everyday hearing difficulties (e.g., problems with communication activities as rated on questionnaires – the HHIE and SAC) compared to the older adults with age-typical hearing (ONHA). Gross group differences in cognitive abilities, however, could not be detected with standard neuropsychological measures. By contrast, some aspects of the evoked electrophysiological data in response to measures of attention differed between groups. The OHL group's elicited responses generally had longer latencies than the ONHA group's responses for the N1 and anterior (but not posterior) P3 components, and, for the OHL group, the N1 latency correlated with an index of speeded visual executive functioning measures from the neuropsychological tests. The pattern of differences in the amplitude of the measured components between the two groups was not as uniform. Specifically, the relative amplitude of the N1 between hemispheres differed between the two groups in that the ONHA group had bigger left than right hemisphere amplitudes and the opposite occurred for the OHL group (and the OHL had less differentiation in amplitude size between hemispheres). Some of the anterior, but not posterior, P3 amplitudes differed between groups. Specifically, the ONHA group showed smaller anterior P3 amplitude for the non-target stimulus in the Redundant task whereas the OHL group did not, indicating a group difference in the ability to sometimes ignore irrelevant information. Overall the OHL group demonstrated differences from typical-hearing older adults in attentional processing that may be generalized in terms of involving extra-auditory processing but are somewhat more specific to the early evaluation of sensory information. The overall pattern of performance on both the N1 and P3 indicate that the older adults with mild hearing loss may not be experiencing an increase in efficiency in their visual processing, but some benefits may arise from their over-processing of information.

5.4.1 Hearing loss and slowing of the N1 and P3

The latency outcome measures provided some evidence of longer processing time for those individuals with hearing loss. The OHL group demonstrated general slowing (i.e., a longer latency compared to the ONHA group) on the N1 on almost all tasks, although these latencies differed statistically from the latencies of the N1 for the ONHA group on the simplest (Simple RT) and most difficult (Complex) tasks only. Moreover, in contrast to the ONHA group, the OHL group's N1 latencies for every task correlated with the index of speeded visual executive functioning calculated from the standard neuropsychological tests. Although the OHL and ONHA groups did not differ on the behavioural cognitive measures in this current study, the significant correlations between speeded visual executive function and the N1 in the OHL group suggest that the efficiency (as measured by time) of the higher-order executive functions have a greater effect on the top-down gating of sensory information (Hopfinger & West, 2006; Luck et al., 1994) for the purpose of selecting currently relevant information in the OHL group on this speeded visual attention task (the FIT). The fact that the correlations were present for all tasks and stimuli may suggest that this top-down reduction in efficiency in the OHL group is somewhat general in nature.

For the P3 component, the latency of the peak amplitude occurred later at the posterior Pz site compared to the anterior Fz site. In comparison to the expectations interpreted from the data on younger participants presented in Chapter 4 (350 – 450 ms), the P3 latency at Pz occurred later for both of these older groups (450 – 600 ms), consistent with previous research in older adults (Reuter et al., 2016). However, there were no statistically detectable differences in posterior P3 latencies between the two older groups of adults with and without mild hearing loss regardless of changes in task demands. By contrast, at the anterior Fz site, the OHL group demonstrated later latencies for most stimuli in the Easy, Complex and Redundant tasks except the Easy and Redundant targets compared to the ONHA group. The ONHA group, on the other hand, only showed a lengthening of latency in response to the most difficult (Complex) task, in a manner that was very similar to the younger adults reported in Chapter 4. Alperin, Tusch, Mott, Holcomb, and Daffner (2015) found that while performing a task, changes in anterior activity occurred before changes in posterior activity. They hypothesized that this anterior activity represented the marshaling of attention to evaluate a stimulus (compared to the later changes in

the posterior P3 that represents stimulus categorization, post-decision monitoring). From this, it would seem that the OHL group took longer in the initial evaluation of most stimuli. In our previous work (Gillingham et al., 2018, Chapter 3), the analysis of the behavioural response times (RT) for these experimental tasks suggested that the OHL group were experiencing a general slowing as shown by the absence of an expected slowing of RT across repetitions of the Simple RT tasks that were administered immediately before and after the binary choice RT tasks (indicative of fatigue or a release from effortful attending), as well as less differentiation in RT between stimuli on the binary choice tasks (although their RT on these binary choice tasks did not differ significantly from the ONHA group). However, analysis of the different foreperiod time intervals (the wait times between stimulus presentations) suggested that the OHL group had a somewhat specific difficulty with the automatic preparation of response rather than a general slowing, possibly related to subcortical areas where motor, sensory, and attention information is integrated in preparation for a response. In the analyses of the ERP responses reported here, the extra time needed in the initial evaluation process may be more evidence of difficulty with early stages of higher-order attentional processing and preparatory activity, as also shown with the correlations of speeded visual executive functioning with the N1 latency. Additionally, the selective shortening of the anterior P3 latencies in response to the target stimuli in the Easy and Redundant tasks by the OHL group, in addition to their ability to improve their strategic responding speeds with more stimulus information that aided discrimination (Gillingham et al., 2018) suggests that there was still some influence of attentional processing on timing rather than this being a situation of completely generalized slowing.

5.4.2 Hearing loss and the N1 amplitude: Inefficiency in early stimulus evaluation

The overall N1 amplitudes did not differ between the OHL and ONHA groups and they showed similar patterns in response to changing task demands. Similar to the results for younger adults in the previous study in Chapter 4, for these older adults the Easy task elicited a larger N1 amplitude in comparison to the other two choice-based tasks. However, the overall smallest amplitude for the older adults occurred for the Complex task (although the amplitudes did not differ between the Complex and Redundant tasks). Based upon the data collected from the younger adults it was expected that the smallest amplitude would occur in response to the

Redundant task which was interpreted to represent suppressive processes (Rorden et al., 2008) since the task instructions explicitly informed participants that the target was separable from the non-targets on all three features. By contrast, the two older groups in the present study had very similar amplitudes for both the Complex and Redundant tasks. Following the interpretation from the study on the younger adults, both of these older groups may not have executed a differentiating amount of control on this early gating process despite task instructions that could guide attention.

Hearing-related differences did occur in the hemispheric asymmetry of the N1 amplitude. The ONHA group had larger amplitudes in the left hemisphere compared to the right. By contrast, the OHL group had generally larger amplitudes in the right hemisphere compared to the left, although the difference between hemispheres was smaller than for the ONHA group. The lateralization differences for the ONHA group may reflect their top-down approach to task completion. The OHNA group's self-report at the end of the study indicated that they used a verbal strategy (internal repetition of features) to maintain attention to the target stimulus. Both feature-based attending (Milivojevic, Corballis, & Hamm, 2008) and verbalization (Grossi, Savill, Thomas, & Thierry, 2010; Maillard et al., 2011; Okumura, Kasai, & Murohashi, 2015; Selpien et al., 2015) implicate left more than right hemisphere processing. This was opposite to the self-report of younger adults who reported visualizing the target and had a larger N1 amplitude in the right hemisphere. Although the OHL group also reported using a more verbal strategy, if there is some form of inefficiency in the top-down influence on this early selection process, as was also suggested by their stronger relationship between standard measures of speeded visual executive functioning and both their N1 latency and N1 amplitude, then they may not be able to capitalize on a more efficient visualization strategy. For the OHL group, the time required to perform complex executive processes appeared to be an important factor associated with this evaluation stage.

5.4.3 Hearing loss and the P3 amplitude: A reduction in control of early (anterior) orientation of attention to irrelevant information but Intact later (posterior) processing

Both older groups showed a typical pattern of larger P3 amplitudes at the posterior Pz compared to anterior Fz electrode site. In our previous study, young adults showed increased

activity at Fz as a function of task complexity. The older groups, however, exhibited increased frontal activity in response to all stimuli and tasks. This suggests that all older adults recruited more processes related to stimulus-driven orientation of attention as is thought to be represented by the anterior P3 (Fjell & Walhovd, 2003; Wild-Wall et al., 2008) regardless of the complexity of the stimulus or task. One exception occurred for the ONHA group, compared to the OHL group, in a context that required some form of control to prevent over-processing of stimulus information. The instructions of the Redundant task explicitly informed participants that the distractors would not share any identifying information with the target stimuli, despite the stimuli being comprised of three identifying features. For the younger adults the lowest amplitudes at Fz occurred on the Redundant task compared to the Easy and Complex tasks. This pattern was interpreted as the suppression or ignoring of unnecessary stimulus information when it was not necessary to evaluate all three features of the stimulus before making a decision. In this study on older adults, compared to the OHL group the ONHA group exhibited a reduction in P3 amplitude at Fz in response to the Redundant non-target in contrast to the amplitude that they displayed to all other stimuli and tasks. This suggests that they may have been able to employ processes related to suppressing the over-evaluation of features for these non-target stimuli. The amplitude for the target stimulus was elevated and comparable to the amplitude in response to other stimuli. It could be that the target stimulus naturally needs more processing due to an inherently different selection process for confirmation plus the fact that it occurred relatively infrequently throughout the task (25% of all stimuli). For the OHL group, the amplitude for the Redundant non-target at Fz was comparable to the amplitudes in the remaining tasks, suggesting that they lack the control of attention shown by the ONHA and younger groups.

The elevated anterior P3 amplitudes fits with other pieces of evidence that the OHL group responded to all stimuli similarly, regardless of context, as assessed by measures that represent relatively early and/or automatic attentional processing in the time between the reception of information and response. This evidence includes longer N1 latencies, a different pattern of hemispheric asymmetry of the N1 amplitude, longer anterior P3 latencies on most stimuli, and previously reported consistent slowing on the behavioural RT of these tasks that was mostly related to automatic response preparation (Gillingham et al., 2018). For the OHL group there is little adjustment as a function of context and they spend more time and resources on processing information.

However, in the context of the Redundant task where there was more information inherent in the stimulus compared to the Easy task, the over-processing may have provided the OHL group with the means to improve response outcomes. As reported in Gillingham et al. (2018), on the Redundant task the OHL group demonstrated faster RTs on trials with the maximum amount of possible time (foreperiod) to strategically prepare for the process of evaluating the impending stimulus and making a response. This was compared to the Easy task where the amount of available preparation time did not provide any benefit to RT (i.e., there were no foreperiod effects), presumably because they had difficulty evaluating and discriminating between the very simple stimuli. We suggested that the improvement in strategic preparation with more stimulus information in the Redundant task provided evidence that there was not a general decline in cognitive function in relation to hearing loss in aging, at least in these participants with mild hearing loss (Gillingham et al., 2018). Likewise, some of the ERP outcome measures (posterior P3 latency and amplitude) did not differ between the OHL and ONHA groups, indicating that there was not a complete generalization of cognitive change as a function of hearing loss. The latency and amplitude of the posteriorly-measured P3, thought to represent processes such as stimulus categorization and post-decision monitoring (Fjell & Walhovd, 2003a; Wild-Wall et al., 2008), were comparable between both groups.

5.4.4 Conclusions

In this study, a visual task of attention elicited a number of modulations in neurophysiological responses in older adults that may correspond to changes in attentional processing associated with mild hearing loss. By administering a visual task, these data support a mechanism of cognitive change that may be associated with the audiometric measurement of hearing loss but that is not limited to auditory-based cognition. This interpretation is most in keeping with the part of the common cause hypothesis (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994) of the hearing loss/cognition connection that states that there is a shared etiology between multiple aspects of sensory and cognitive decline, although we cannot provide evidence for the other part of the hypothesis that states that the link between a change in sensation and a change in cognition is non-directional/non-causative. However, although there may be evidence of a shared etiology, our data across two studies also suggest that the effects associated with mild audiometric hearing loss are specific to particular aspects of cognition (this

current study and Gillingham et al., 2018). Compared to older adults with age-typical hearing, the older adults with mild hearing loss differed on measures of relatively early/automatic attentional processes that affect speed and preparatory abilities (e.g., slowed attentional guiding and visual discrimination represented by the N1 and anterior P3, a lack of top-down suppression of unnecessary information as represented by the heightened anterior P3 amplitude, and impaired automatic response preparation represented by the analysis of RTs associated with different foreperiods). By contrast, the OHL group showed relatively intact strategic response preparation under certain conditions and was also comparable to the ONHA group on their relatively later attentional processes represented by the posterior P3 amplitudes and latencies.

The results indicated that the OHL group was not experiencing an increase in efficiency in visual processing (latencies of the N1 and anterior P3, similar N1 amplitudes between hemispheres) and they recruited more attentional processes than the ONHA group as represented by the anterior P3 amplitude. It could be argued that these results indicate that the OHL group may be able to adaptively recruit resources that helped them respond outwardly in a similar manner as the ONHA group, which could explain the lack of difference between the two groups of older adults on standard cognitive measures. However, given that there is evidence of slowing on the simplest RT tasks and an interruption of automatic, and sometimes strategic, response preparation, overall the results show that there are at least some aspects of cognitive processing in the OHL group that can be described as more effortful than the ONHA group, even if the end result is comparable outward functioning between both groups. There is one instance where the change in processing may have benefitted the OHL group. Their RT data on the Redundant task suggested that they were able to utilize the extra stimulus information in this task to regain strategic response preparation abilities (Gillingham et al., 2018). Therefore, the over-recruitment of attentional processes in this task when they could have instead ignored extra information in the stimulus may have benefitted them. Future studies will have to assess if the extra recruitment of attentive processes is a form of adaptive functioning in the context of hearing loss or if the extra recruitment of attentive processes represents a decline in functioning and the benefit to RT just occurred secondarily in the context of the particular demands of the Redundant task.

Chapter 6

General Discussion

6 General discussion

6.1 Summary of findings

A set of visual attention tasks with no explicit auditory or language component was used to examine the sense-specificity of the sensory-cognition relationship in aging and hearing loss. The tasks were administered in a pre-defined order so that they presented participants with changing task demands that were hypothesized to introduce additional attentional processes with each successive task. This allowed for the inclusion of an assessment of simple processes in contrast to most previous literature that often included more complex and working memory-heavy task demands. The tasks used were also validated in previous literature as sensitive to multiple attentional processes involving anterior, or frontal lobe, functioning. In combination with EEG, this allowed for the assessment of the possibility of compensatory changes in processes related to early sensory evaluation and the recruitment of frontal attentional processes as was suggested by literature in middle-aged adults with hearing loss but was unexplored in older adults. Finally, much of the knowledge of the connection between hearing loss and cognitive decline in older adults has come from studies involving older adults with measurable cognitive decline and also potentially functional decline. This set of studies examined older adults who were cognitively and functionally healthy by self-report and by the results of standard measures of cognition. This allowed for the assessment of the possibility of changes in visual cognition occurring in conjunction with mild hearing loss at an early stage. The results across three studies demonstrated that cognitively-intact older adults with mild hearing loss differed in: i) response time on the simplest tasks and automatic preparatory processes compared to younger adults and older adults with age-typical hearing; and ii) ERP indices of sensory-cognition integration and early attentional guiding compared to older adults with age-typical hearing.

The purpose of the first study was to compare visual attentional processing in older adults with mild hearing loss (OHL) against that of older adults with age-normal hearing (ONHA) and younger adults (YN). This was carried out by analyzing the behavioural RT data from visual reaction time (RT) tasks that increased in complexity, and thus in the requirement for attentional resources, both within and across tasks. The results showed deficits in attention and response preparation processes in older adults with mild hearing loss that were not observed in younger or

older adults who had better hearing thresholds. Indicators of attention-related differences in the OHL compared to the ONHA group were observed on the simplest of tasks (generalized slowing, a lack of change in the RT response in the context of fatigue or a release from effortful attending). Additionally, the continued disruption of automatic response preparatory abilities while strategic preparatory abilities improved when there was more stimulus information to attend to (Redundant task) highlighted possible disruptions in automatic timing processes that underlie higher cognitive functions. These results indicate that there may be some common disruptions in neural processes that affect multiple systems underlying cognitive changes that have been previously observed in hearing loss in older adults. These results also suggest that, although there may be involvement of multiple sensory and motor systems as would be expected by the common cause hypothesis, the effects on behaviour may not be fully generalized as the OHL group exhibited intact strategic attentional abilities under certain contexts (e.g., intact variable FP effect in the Simple and Redundant tasks). In this case, the interaction between the neural disruptions and measurable effects on higher order cognitive functions may depend on variables such as age of onset and time since onset of hearing loss and genetic or environmental factors affecting neuronal health.

The purpose of the second study was to characterize the neural correlates of the FIT tasks using EEG in young adults as a normative study. The N1 and P3 were chosen as well-known representations of relatively early attention-based sensory selection (N1) and late attention-based response selection (P3) processes that are sensitive to changing task demands and the recruitment of attentional processes. These components provided a means to evaluate changes in early visual functioning and the recruitment of hypothesized anterior (frontal lobe) attentional processes which could help provide insight into how visual processing changes in the context of hearing loss (e.g., a loss of function and/or compensatory functioning). It was expected that the combination of the visual task and EEG would provide a set of outcome metrics that would be useful for studying clinical contexts where slight changes in attentional processing were hypothesized to be taking place, such as with mild hearing loss. Task demands influenced the latency and amplitude of the N1 and P3 waves, the anterior-to-posterior distribution of the P3 amplitude, and the patterns of modeled sources of peak neural activity. Increases in complexity relating to difficulty discriminating between stimuli for a binary choice relied increasingly on anterior attentional resources, especially for the identification of infrequent target stimuli. The

presence of distracting information relied on anterior attentional resources to suppress unnecessary information, and this inhibitory ability was particularly sensitive to individual differences in performance.

The purpose of the third study was to use the combination of the FIT tasks and EEG to examine the neural correlates of visual attention in the context of changing task demands and mild hearing loss in aging. In addition to the pure-tone hearing thresholds that were used to categorize the two groups of participants, the older adults with mild hearing loss (OHL) significantly differed from the older adults with age-typical hearing (ONHA) in terms of their (reduced) ability to hear speech in ‘noise’ (a crowd) and their self-reported measures of practical, everyday hearing difficulties (e.g., problems with communication activities). Group differences in cognitive abilities, however, could not be detected with standard neuropsychological measures. By contrast to the neuropsychological tests but consistent with group differences on the auditory measures, some aspects of the evoked electrophysiological data were unique to the older adults with mild hearing loss. The OHL group’s elicited responses were generally slower than the ONHA group’s responses for the N1 and anterior (but not posterior) P3 components, and the N1 latencies correlated with their speeded visual executive functioning measures from the neuropsychological tests. For amplitude, the relative size of the N1 amplitude between hemispheres differed between the two groups (ONHA had larger amplitudes in the left compared to right hemisphere whereas the OHL group had near equal amplitudes between both hemispheres) which may be suggestive of differences in top-down approaches to analyzing the relatively early visual information. The ONHA group also showed smaller anterior P3 amplitude in response to the non-target stimulus in the Redundant task whereas the OHL group did not. This suggests that the OHL group did not ignore or suppress unnecessary information. There were no differences between the groups on posterior P3 amplitude size. Overall the OHL group demonstrated differences from typical-hearing older adults in attentional processing that may be generalized in terms of involving somewhat slower processing abilities and an over-recruitment of anterior attentional abilities, but not all aspects of cognition are compromised. It may be that, in the context of hearing loss, the differences in processing exhibited by the OHL group is adaptive in that it allows them to maintain comparable levels of functioning to the ONHA group as shown by the equivalent scores on standard neuropsychological measures between both groups. However, the evidence of slowing on the simple RT tasks as well as disruptions in

automatic response preparation and recovery shows that there is still at least a cost to their overall cognitive processing as a function of hearing loss.

6.2 Hearing loss and visual attention in aging

These studies used multiple tasks that assessed different aspects of attention with changes in task demands in each successive task. This sequential incorporation of different attentional processes allowed for the comparative assessment of various levels of attentional functioning between older adults with and without mild hearing loss. The older adults with hearing loss demonstrated slowing as shown by the behavioural RTs that was most detectable on the simplest tasks. This is notable considering that older adults without hearing loss have been shown to perform almost as well as younger adults on both simple and complex cognitive tasks (Guerreiro & Van Gerven, 2017), although it is important to consider age-related declines in sensory stimulus discrimination for such evaluations (Murphy, Schneider, Speranza, & Moraglia, 2006). However, the data across two studies suggest that the effects associated with hearing loss are not completely generalized. The OHL group differed from the ONHA group mostly on the processes that affect sensory-cognitive integration and automatic preparatory abilities (e.g., slowed attentional guiding and visual discrimination represented by the anterior P3 and N1 latencies, a lack of top-down suppression of unnecessary information as represented by the anterior P3 amplitude, and impaired automatic response preparation represented by the analysis of RTs associated with different foreperiods). By contrast, the OHL group showed relatively intact strategic response preparation on the behavioural RT data comparable to both the ONHA group and younger participants under conditions where there was no requirement to discriminate between different stimuli or where stimulus discrimination was necessary but based upon multiple, and helpful, identifying features (a process known to be controlled by the frontal lobes; Gillingham et al., 2018; Stuss et al., 2005; Vallesi et al., 2007a). They were also comparable to the ONHA group on the attentional processes represented in the ERP data by the posterior P3 amplitudes and latencies that occurred relatively later compared to the N1 and anterior P3 (Gillingham et al., 2018). The preservation of later and more voluntary cognitive processes makes sense given the relative similarity between both groups of people in terms of their

recruitment as healthy individuals from the community, and may also explain the lack of measurable differences in performance on standard neuropsychological measures.

The data from these studies offer support for a possible common cause. However, by studying early-stage hearing loss, these data are also supportive of the idea that there is still some specificity, at least at this early stage of hearing loss, in the cognitive processes associated with hearing loss because the OHL group did not differ from the ONHA group on all outcome measures.

Another purpose of this study was to assess if any changes in visual cognition represent a loss of function or a compensatory change in function. Compared to the ONHA group, the OHL group showed increases in N1 latency and N1 amplitude that were correlated with their performance on standard measures of speeded visual executive functioning. This suggests that, at this early stage of visual processing, the OHL group did not show an increase in efficiency (shorter N1 latencies) as was shown by middle-aged adults with mild hearing loss (Campbell & Sharma, 2014). Instead their performance is indicative of a decrease in efficiency in early visual processing and an increased association with higher attentional processing compared to normal hearing adults. We also hypothesized that the OHL group may show greater P3 amplitudes measured from anterior electrodes (often interpreted to represent more anterior, frontal lobe-based attention processes) compared to the ONHA group. This hypothesis was based upon previous research showing that middle-aged adults with mild hearing loss recruit more frontal regions for listening tasks compared to their hearing-normal peers (Campbell & Sharma, 2014) and also on research that suggests that well-known aging effects (such as the recruitment of frontal brain regions in aging) may be driven by unidentified hearing loss in population samples (Guerreiro & Van Gerven, 2015). In the present study, all older adults, regardless of hearing ability, had elevated anterior P3 amplitudes thought to be related to anterior (frontal) attention, which was a different result than that observed in a study of younger adults who showed more differentiation in amplitude based upon task and stimulus complexity. The one exception involved the apparent ability of the ONHA group to inhibit unnecessary information in some circumstances (represented by a relative decrease in anterior P3 amplitude), similar to that shown by the younger adults. By contrast, the OHL group showed elevated amplitudes even in contexts where they were explicitly instructed that unnecessary information would be present in the stimuli (Redundant task). Therefore, although the recruitment of anterior attentional processes

may be somewhat of a general aging effect, there were some differences in the recruitment of these anterior processes between these older groups of participants who differed based upon hearing thresholds.

This over-processing by the OHL group may not necessarily represent a decline in functioning for these older adults with mild hearing loss, especially when they did not subjectively report any difficulty with daily functional cognition. They did demonstrate some general slowing on the RT analysis (Gillingham et al., 2018). However, an increase in baseline or general RT is not necessarily related to all of the multiple anterior (frontal lobe) functions that may be recruited as a part of cognitive processing (Stuss & Alexander, 2007). The OHL group did show a return of strategic response preparation as shown in the foreperiod analysis in the Redundant task after this type of response preparation was not observable in the previously administered Easy task (Gillingham et al., 2018). This was interpreted as their ability to strategically use the extra information in that task's stimuli to improve RT performance when they had an appropriate amount of time to prepare (a largely executive-type frontal lobe process). In this context, the over-processing in the Redundant task seen in the ERP data may be viewed as a form of compensatory processing that allowed for improved performance despite the possibility of a reduction in functioning that led to overall slowing in the pathway between sensory reception and response.

Future research is needed to examine if the compensatory processing occurs as an adaptive change in the face of decline elsewhere in neural/cognitive functioning or if it occurs as a serendipitous consequence of changes (declines) in functioning relating to hearing loss. That is, are these older adults with mild hearing loss strategically increasing their visual processing of all information in order to compensate for negative changes occurring in response to hearing loss, or are these older adults experiencing faster RTs in certain conditions just as an unintended positive consequence of their inability to suppress selective visual information? A recent paper by Wettstein et al. (2018) showed that there was a positive correlation between visual resolution abilities and performance on standard measures of cognitive functioning in older adults with at least moderate hearing loss. [There was no correlation between visual resolution and cognitive performance in adults with mild hearing loss as studied here.] As noted by Wettstein et al., compensation was hypothesized to occur as a by-product of the maintenance of visual resolution and cognitive functioning rather than as an adaptive response that resulted in a gain in visual

functioning. That is, if the older adults with hearing loss happened to have maintained visual functioning then cognitive functioning was also more likely to be maintained as well. With this visual-cognition relationship, Wettstein and colleagues hypothesized that the maintenance of visual functioning may have promoted the maintenance of cognitive functioning due to the allowance of a person to continue participation in cognitively stimulating activities by using their visual sensory system. In the case of the older adults with mild hearing loss in our studies, although they appear to have an ability to employ strategic processing that was shown by their performance on measures of strategic response preparation in RT and on standard measures of cognition, further study is required to assess if these are abilities that maintained due to compensatory processing or are maintained as a serendipitous side effect of declining functioning (e.g., faster responses in certain contexts due to over-processing).

6.2.1 Explanations for an association between changes in hearing and cognition

The results of the studies presented here could be interpreted as giving support to the common cause explanation of the association between hearing loss and cognition. An original tenet of the common cause hypothesis states that cognitive and sensory decline occur simultaneously and by the same mechanism such as through neurodegeneration without directionality in terms of cause. However, the current studies were designed to test the hypothesis that changes in basic aspects of cognition, specifically relating to attention, could be measurable using a non-auditory modality in the context of mild hearing loss as the main feature differentiating two groups of older adults. That is, these studies set out to test the hypothesis that there was a connection between hearing loss and visual cognition without specifically testing the issue of directionality underlying the etiology of the sensory/cognitive association (i.e., where the connection originated or progressed from). Therefore, these results do not negate the principles of the remaining hypotheses that exist (e.g., sensory deprivation, cognitive load). There is some evidence from longitudinal studies of a sequential order to the appearance of sensory and cognitive decline (i.e., sensory loss precedes or even leads to cognitive loss or vice versa in the context of a common change in cognition).

However, considering this present supportive evidence of a possible common (although not completely generalized) association between hearing loss and a change in cognition, the

question of why and/or how such an association exists needs to be addressed. There are multiple layers to this question, the first of which relates to how to define hearing loss. This current set of studies attempted to recruit and categorize participants based upon hearing loss assessed by pure-tone thresholds and the tasks involved in the research did not involve higher-order auditory processing. The early reports of clinical indicators of cognitive decline connected to sensory loss did include a reduction in multiple primary sensory and motor abilities (reviewed in Albers et al., 2015). However, as reviewed in the general introduction, some research suggests that hearing loss as we typically measure it clinically via the pure-tone threshold is not the best predictor of real-life auditory functioning (Gordon-Salant, 2005; Houtgast & Festen, 2008; Pienkowski, 2017; Tremblay & Backer, 2016). This would suggest that threshold sensory loss may not necessarily be the biggest concern. However, the majority of studies and predictive modeling approaches suggest that it is peripheral (as usually measured by pure-tone threshold) hearing loss that starts around mid-life that is a significant predictor of subsequent cognitive decline (Livingston et al., 2017). Therefore considerations for mechanisms are limited to the assumption that auditory thresholds can be an important element at least in the early stages of a potential sensory/cognitive connection, keeping in mind the caveat that there are many other mechanisms of change in the peripheral and central auditory system that can underlie hearing loss.

This current set of studies suggests that threshold hearing loss is associated with changes in the processing of incoming information from non-auditory (visual) sensory domains. Additionally, compared to the participants with age-typical hearing, the participants with mild hearing loss in the current studies did have a reduction in motor functioning in their non-dominant hand as measured by a finger tapping task and in their visual contrast abilities (although this was a non-significant difference between the two groups). So while we categorized participants based upon hearing loss which was measurably different between the two groups, there was also some suggestion of reduced functioning in the visual and motor systems of the participants with mild hearing loss. It would be difficult to equate the changes in the different sensory and motor systems so we do not know if the amount of change that we observed between the OHL and ONHA groups in the motor and visual systems is quantifiably equivalent to the amount of change between the groups in the auditory system. This may especially be the case if we consider that we may typically intervene in motor and vision changes at a much earlier age and more readily than we do with auditory changes. For example, for

finger-tapping, the two older groups of participants only differed on the non-dominant (left) hand. This suggests that there may only be a reduction of functioning in the case where practice for motor control likely occurs less often, or perhaps that practice with the dominant hand prevented measurable decline in that hand. As for the visual system, many participants reported using some form of sensory aid (e.g., glasses) and/or corrective surgery (e.g., cataracts). By contrast, the eligibility criteria for the participants with mild hearing loss included their not having tried any form of intervention for hearing loss (some of them had had previous clinical audiograms and were told that their hearing loss was mild with no requirement for intervention). Even though there is as of yet no strong evidence that interventions such as hearing aids help to improve cognition (Livingston et al., 2017), it is much more common for people to utilize visual interventions starting much earlier in life. It therefore must be considered that early and continued intervention might play some role in preserving the visual system that possibly stands in contrast to typical approaches to the auditory system. So while hearing loss was the primary measure of sensory change that was measurably different between the two groups of older adults, there actually may have been some multisensory involvement to some extent.

We cannot say that the data from this current set of studies fully supports the common cause hypothesis because we still have not tested whether there is a directionality component to the connection (i.e., one may have preceded and led to the other). We just have evidence that threshold hearing loss is associated with visual attentional processing that is different from that of people with age-typical hearing. However, one of the main goals behind the development of these studies was to assess people with very mild stage hearing loss who did not exhibit cognitive difficulties as measured by standard neuropsychological tests. In this context, we demonstrated that although there may be a ‘common’ connection between sensory loss and a change in attentional processing using what we think is a more sensitive assessment tool, there was some specificity to the types of changes in attentional processing associated with mild hearing loss (i.e., it is not just a complete general decline in functioning).

We are therefore left to propose a possible mechanism to explain how threshold hearing loss may be associated with changes in relatively early attentional processes relating to the timing of the integration of attention with incoming sensory information for stimulus selection/identification, information suppression, and automatic response preparation. One of the gaps in the research that we were attempting to address in the establishment of this set of studies

was the need for research in people with early-stage hearing loss who did not have any indication of cognitive or functional loss. The necessity for this research stems from the fact that when we study people who already have dementia, there are so many confounding factors that it is difficult to establish a mechanism for the sensory-cognitive association. However, in studying early-stage hearing loss, we then also have to present the caveats underlying any proposal for a mechanism as: i) we do not yet know if the changes in cognition that we see in the results of these studies are meaningful with respect to representing a necessary early-stage progression toward neurodegeneration and cognitive decline, and ii) there is almost an unintended assumption that any proposed mechanism may be underlying an important pathway of progressive neurodegeneration of at least one type of dementia, if not more, although we are still limited in our knowledge of the type(s) of dementia most associated with hearing loss. Many of the early clinical observations and subsequent research has focused on Alzheimer's disease, although a recent meta-analytic review of a small number of studies (fourteen) suggests that dementia type does not modify the observable connection between hearing loss and dementia (Ford et al., 2018).

The particular set of attentional processes that showed the greatest change as a function of hearing loss in this set of results were processes that represented relatively early (in timing of the progression of attention from the reception of sensory information to the production of a response) and automatic functions. For participants with mild hearing loss, in comparison to the age-typical hearing participants (and to the younger adult participants for points i and ii), it could be inferred from the findings that:

- i) they had somewhat of a slowed and uniform timing of response in situations where higher-order attentional processes were not engaged (the slowed but equal response times between repeated blocks of Simple RT without any expected effects of fatigue or releasing from effortful attending).
- ii) they had more consistent difficulty with automatic response preparation (the sequential foreperiod),
- iii) they took longer to integrate the incoming sensory information with their top down attentional control of feature categorization (N1 latency),

- iv) they may have been somewhat less efficient in employing attentional control at the N1 sensory/attention integration stage (less lateralization of the N1 amplitude and correlation of N1 latency and amplitude with speeded visual executive processing), and
- v) they did not employ any suppressing or inhibitory processes to help filter unnecessary information (amplitude of the anterior P3 in the Redundant task).

By contrast, these same participants demonstrated comparable (to the i) younger adults and age-typical hearing older adults and ii) just the older adults) outcomes representing relatively later attentional processing such as:

- i) strategic or voluntary response preparation, especially when there was enough information provided in the stimulus for them to evaluate or make a response (variable foreperiod, Simple and Redundant RT tasks), and
- ii) the overall evaluation and categorization of a stimulus (posterior P3 latency and amplitude).

Thus, the defining characteristics of the pattern of results that set the participants with mild hearing loss apart from the participants with age-typical hearing was the disruption in early or automatic attentional processes using tasks tapping non-auditory cognition. Although there was evidence of an increase in anterior attentional processing, some of the executive-type processes (e.g., strategic response preparation) were relatively intact. There are two main possibilities that may then best explain the current results, although they are not mutually exclusive. The first possibility is that there is a change in functioning, possibly within a localized area, within the subcortical regions that integrate and relay bottom-up and top-down information in the early reception and perceptual stages. This could possibly implicate areas such as the thalamus and basal ganglia (Cappe et al., 2009), and the associated projecting pathways to cortical areas.

A second, and potentially related possibility, is that there may be a disruption between functional networks affecting early and automatic aspects of attentional processing in mild hearing loss. Using language-based tasks, Campbell and colleagues (2016) examined the change

in functionality of brain networks with respect to the integrity of their within-network versus between-network connections as a function of age. The within-network connectivity of singular networks that were activated in response to simple language comprehension without the requirement of a response (e.g., auditory syntax network, frontotemporal syntax network) was comparable between healthy younger and older adults. An age-related difference did occur, however, in between-network connectivity when more networks were recruited during task performance (i.e., an acceptability judgment). Older adults showed a decrease in the flexible interaction between networks, although overt performance was unaffected and seemed to be related to crystallized verbal knowledge that acted as a compensatory mechanism.

A recent functional imaging study in middle-aged (mean age of 56) adults with at least one year of bilateral sensorineural hearing loss as measured by pure-tone audiometry compared to controls assessed connections between the insula (known for multimodal sensory processing) and other brain regions (Xu et al., 2019). The results showed that, for the participants with hearing loss, there was hyperperfusion in the insula and also decreased functional connectivity between some subdivisions of the insula and the thalamus, putamen, precentral gyrus, postcentral gyrus, mid-cingulate cortex, dorsolateral prefrontal cortex, and the rolandic operculum. Declines in the strength of the functional connections were correlated with declines in scores on assessments of emotion, anxiety, and cognition. Additionally, there were abnormal interactions among the salience, default mode, and central executive networks. This provides support for the idea that the functioning of sensorimotor integration areas may be important for understanding the association between sensory and cognitive functioning, although it is important to note that this study was performed in younger participants compared to the participants in this set of studies, and further research would be needed to assess if the same types of changes in functional connectivity would occur in older adults.

In consideration for a potential relationship between the involvement of subcortical integration areas and/or networks and the development of dementia, various imaging studies have shown that subcortical structures such as the thalamus, putamen, caudate, and amygdala, in addition to the expected hippocampal regions, are implicated in Alzheimer's disease with respect to pathology (Braak & Braak, 1990, 1991; Knight et al., 2011), volume loss (Cherubini et al., 2010; de Jong, et al., 2008; Wang et al., 2018), and diffusion imaging (Wang et al., 2018). Further still, imaging studies have shown that changes in subcortical structures are positively

correlated with the severity of the disease (Roh et al., 2011; Wang et al., 2018). The exploration of Alzheimer's disease as a 'disconnection syndrome' (Geschwind, 1965) has shown that, compared to neurologically healthy older adults, people with Alzheimer's disease have changes in functional connectivity (although not necessarily a reduction) *within* the default mode network (Binnewijzend et al., 2012; Toussaint et al., 2014; Zhong et al., 2014) and various resting state networks (Agosta, Caso, & Filippi, 2013; Castellazzi et al., 2014; Song et al., 2013; Zhao et al., 2012). There is also evidence that both functional and structural changes (e.g., degradation of white matter tracks that connect brain regions) within networks appear in advanced stages of the disease (i.e., dementia) whereas functional changes are more prominent than structural changes in prodromal stages (i.e., MCI; Palesi et al., 2016). By extension, it may also then be possible that changes are occurring in subcortical structures or in the functional connections between networks before the clinical presentation of a syndrome (either mild cognitive impairment or dementia) that may be manifested in changes in sensory, cognitive, and possibly motor functioning.

6.3 Future directions

The studies presented here used multiple attention measures with different task demands. This allowed for the demonstration of consistency in performance across multiple outcome measures that differentiated changes in attention between older adults with and without mild hearing loss. In addition to replication, future research can include more diverse samples, including investigating whether the effects seen here are related to the same sensory-cognitive changes noted in even earlier-onset hearing loss (Livingston et al., 2007) and to assess if these changes are actually meaningfully related to future cognitive decline. This is especially important given the evidence of there being multiple contributions to hearing loss in aging within the peripheral and central aspects of auditory processing that may be acting somewhat independently, at least in neurologically healthy older adults (Profant et al., 2019). The interpretations provided for these studies that implicate the involvement of sensory-motor-cognitive integration areas in older participants with mildly elevated pure-tone thresholds during visual processing may not be meaningfully related to difficulties seen with the central aspects of complex auditory processing that is often observed in auditory-based studies of hearing loss in

aging. The tasks used in this set of studies involved response time and so any significant findings suggest that the speed of attentional processing is implicated. However, response speed was still beneficially influenced by the type of attentional processes targeted (e.g., the reappearance of intact strategic response preparation – the speeding up of a response - in the Redundant task with the more involved stimuli). Interpretations therefore used the pattern of response times to suggest that certain brain regions (e.g., subcortical) may be implicated more than others (e.g., right frontal cortex). Further research is required to assess if it is the *speeded* component of attentional processing that is key to highlighting changes that may be occurring in the context of sensory loss, as has been suggested in some of the auditory-based research. Similarly, the words inhibition and suppression have been used here in reference to some of the differences in attentional responding that was demonstrated by the OHL group, especially in comparison to the ONHA group (e.g., they may not have been suppressing attention toward the unnecessary stimulus information in the Redundant task). More research is required to assess if the processes involved here that underlie this apparent lack of suppression or inhibition may also be related to similar processes suggested in auditory-based research (e.g., a reduction in inhibitory interneurons).

This current set of studies furthered our understanding of the specificity of the timing and source localization of the attentional processes in the healthy brain and provided potential outcome measurements for their quantification in assessing clinically relevant changes in brain health. However, future research is needed to further refine outcome measures to assess the early and automatic aspects of attention and sensory-motor-cognitive integration rather than just higher-order cognitive functions that may be more reliant on cortical functioning. Additionally, research is needed to assess whether or not the problems demonstrated here by the participants with mild hearing loss represent one mechanism of change or several separable mechanisms that seem to have a somewhat general effect on our measurements of response preparation, early stimulus evaluation, and the over-recruitment (and lack of control of) anterior attentional processes.

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