Electroencephalography shows effects of age in response to oddball auditory signals: Implications for semi-autonomous vehicle alerting systems for older drivers.

by

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Abstract

This research considers the efficacy of auditory alert systems for semi-autonomous vehicles from the perspective of the neurological processing of multi-modal information. While semi-autonomous vehicles are growing in popularity, there is much to be discovered concerning driver safety. For example, understanding how the brain integrates multi-model information is essential to determining the efficacy of auditory alerting systems in semi-autonomous vehicles. The present work reports on how the auditory processing of deviant and standard stimuli is impacted by age and workload conditions at regions of the brain involved in the auditory processing pipeline. Electroencephalography (EEG) and behavioural data from five older (57-78) and five younger (18-26) participants were collected. Participants completed a visual memory task with low- and high-workload conditions along with a novel paired-click paradigm. Behavioural results showed the expected negative effects of age on visual task accuracy and response times. EEG results showed that in the low-workload visual task condition both younger and older adults partially overcame the redundancy effect of the second paired tone when a highly salient stimulus was presented. In contrast, P200 neural responses to these oddball tones were attenuated in older adults in the high-workload conditions of the visual memory task. These findings have implications for how alerting systems are implemented in semi-autonomous vehicles.

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Chapter 1: Introduction

As autopilot features in semi-autonomous vehicles become more widespread, questions regarding drivers' required level of task awareness become increasingly important. At present, semi-autonomous vehicles available to the public demand that users remain engaged in driving tasks to perceive and efficiently act on driver safety alerts (Knoefel et al., 2019). Such alerts indicate disengagements with autopilot, also known as handovers, where the driver assumes control of the automation system (McCall et al., 2019). Individual factors, such as age and driver experience, affect how alerts are detected and impact driver behaviour. These individual factors, coupled with the human tendency to become distracted during driving, and finally, the lack of clarity surrounding semi-autonomous vehicles and operator involvement, suggest a better understanding of driving alerting features and their efficacy is necessary. The present research examined auditory sensory gating during neurological processing of visual information. The findings from the present research can be used to inform decisions regarding the design and implementation of driver alert systems in semi-autonomous vehicles.

Semi-autonomous vehicles will directly impact the future of transportation, particularly once full autonomy has been achieved and human interference is not required. That said, the integration of fully autonomous vehicles into the fleet is decades away, and humans remain an essential part of the driving operation (Litman, 2021). Despite the need to keep the human in the loop, drivers are less engaged in autopilot driving tasks than is recommended by manufacturers (Morando et al., 2020). Furthermore, while in autopilot, drivers are more susceptible to fatigue and engaging in secondary tasks (Jamson et al., 2013; Morando et al., 2020). Secondary, non-driving tasks distract drivers from the primary responsibility of maintaining a safe driving interaction and may include text messaging, talking to another passenger, or interacting with the in-vehicle information system (Jin et al., 2018). Semi-autonomous vehicles have integrated auditory alerting systems to redirect driver attention, and these sounds are often activated during high-risk events, particularly those that require immediate driver action. However, little is known empirically regarding the effectiveness of these alerts and whether they have the necessary salience to redirect attention across a wide age range of drivers. The key issue is that most vehicle sounds are actively filtered, or "gated", away from driver attention by neural functions that allow the driver to focus on the primarily visual task of driving. The present research considers the efficacy of auditory alerts from the perspective of the neurological processing of multiple modes of information (auditory and visual). Understanding the impact of processing multiple modes of information simultaneously is essential to determining the efficacy of auditory alerting systems in semi-autonomous vehicles. Investigating how younger and older groups process various auditory stimuli while engaged in visual memory tasks with different workload levels is a critical step in optimizing safety in semi-autonomous vehicles. Using electroencephalography (EEG), this research examined the neurological processing of standard and deviant tones in the brain's auditory processing pipeline. The effects of older age on the processing of these auditory tones were also examined for these key brain regions. A central design factor in this work was the novel integration of two well-established EEG protocols: the paired-click (two tones in quick succession) and oddball (standard and deviant tone comparisons) paradigms. This EEG experiment was designed so that the auditory stimuli of interest (the redundant second tones) were compared with matched redundant tones that differed only in their salience. The experimental protocol imitated real-life driving situations where auditory alerts occur within a noise-laden and, thus, filtered background of auditory stimuli. Notably, the passive tones (not requiring a response) were presented alongside a primary visual memory task that ensured that participants were simultaneously engaged in complex visual processing and decision making.

Chapter 2: Literature Review

The following sections discuss the current state of semi-autonomous vehicles and their auditory alerting systems, emergency handover scenarios, as well as how age and workload impact auditory processing. The neurophysiological aspects of this research are also discussed, including the utility of the P200 component of the auditory event-related potential (ERP) as an index of the effects of age and visual memory workload on salient auditory stimuli.

2.1 Semi-Autonomous Vehicles

According to the Society of Automotive Engineers On-Road Automated Vehicle Standards Committee, there are six levels of automation, ranging from Level 0, no automation, to Level 6, fully automated (2018). Levels 0 – 2 require the driver to be fully engaged in the task of driving, while Levels 3 – 5 are less clear about the degree of focus drivers require. Only Level 2 semi-autonomous vehicles are currently available for public use, with more advanced semi-autonomous vehicles remaining prototypes or concepts (Banks et al., 2018). As such, most of the literature included in this research will cover Level 2 semi-autonomous vehicles. Nonetheless, this research is highly relevant for semi-autonomous vehicles falling into Levels 3 and 4, mainly because these levels require that drivers are engaged enough to perceive and act on alerts (Knoefel et al., 2019), which is an ambiguous definition, to say the least.

Alerts in semi-autonomous vehicles include both visual and auditory stimuli. The literature indicates that the most common alerts found in a Level 2 semi-autonomous vehicle (Tesla Model S) include visual and auditory alerts for different scenarios (Banks et al., 2018). Such alerts include the following: notification to control the steering wheel (visual alert when low urgency, visual and auditory alert when urgency is high), warning of an impending collision (visual and auditory alert) or a notification that the user must immediately take over the driving task (visual and auditory alert). Seemingly, more urgent warnings include both visual and aural alerts, which further solidifies the importance of understanding how auditory alerts are processed during visually demanding tasks, such as driving.

2.1.1 Handover Tasks and Disengagement

This research focuses on the moments leading up to disengagements with autopilot, otherwise known as handovers (McCall et al., 2019). Disengagement involves any instance whereby users are prompted through auditory and visual cues to take over the driving task. Some reasons for disengagement include software issues, inclement weather, or user judgement (Lv et al., 2018).

Handovers require some level of attention from the driver, and the increasing number of distractors available may compromise safe handover operations. In a simulator study by Carsten et al. (2012), participants were evaluated across three levels of autonomous vehicles to determine the likelihood of secondary task engagement. The level of autonomy included completely manual (no automation), semi-automated, and highly automated vehicles. Participants were presented with different activities to engage in only if they were inclined to do so. Some of the tasks consisted of eating, playing a game, or reading. They found that as the level of automation increased, secondary task involvement also rose. This finding is a safety concern given the tendency for automated vehicles to disengage or require operator intervention.

The State of California Department of Motor Vehicles (2019) has an Autonomous Vehicle Testing program where semi-autonomous vehicle manufacturers must provide an annual disengagement report. These reports detail the reason for disengagement and incidence rate, as well as the distance (in miles) test-driven in autopilot. Dividing the number of miles driven in autopilot by the number of disengagements experienced yields the distance driven per disengagement (Lv et al., 2018). Following the application of this calculation to the 2019 Disengagement Report, it grew clear that disengagement rates vary based on the manufacturer and should be cause for concern. While the values cannot be compared, as there was no control for test-driving in autopilot between manufacturers, the outcomes were still of interest. Mercedes Benz Research and Development North America reported that in 14238 miles test-driven, 2054 disengagements occurred, roughly translating into one disengagement every 6.9 miles. Furthermore, Aurora Innovation Incorporated reported that of 13429 miles test-driven, 141 disengagements occurred, which approximates to one disengagement every 95 miles. These inconsistencies further verify that while semi-autonomous vehicles are improving, the improvements are not widespread, and human assistance is still necessary.

2.1.2 Semi-Autonomous Vehicle Auditory Alert Systems

Auditory alerting systems in vehicles have long been considered superior to visual alerting systems for their passive and easy to receive nature (Wogalter et al., 2002). While auditory alerts are standard practice in all vehicles, semi-autonomous vehicle manufacturers implement various forms of alerts, from standard tones to multi-tone alerts, repetitive chimes, and even speech messages (Nees et al., 2016).

In addition to auditory alerts, in an on-road driving task, it is guaranteed that there will be some level of interior noise in the form of engine, road, and aerodynamic noise, to name a few (Harrison, 2004). Moreover, there are likely to be task-irrelevant sounds contributing to the interior noise, such as other passengers, vehicles, music, or auditory notifications from mobile phones. The literature suggests that internal noise within vehicles ranges from 100 and 4000 Hz (Au, 2011), and considering this, the loudness of any auditory alert systems is an important factor in vehicle safety. In a virtual reality driving study, participants engaged in a highway driving scenario where they were presented with various auditory alert signals of different loudness (Lin et al., 2009). This study found that alerts at a frequency of 1750 Hz were significantly more successful in reducing poor driving behaviours than alerts at both 500 Hz and 3000 Hz.

There has been some research conducted on the position of auditory signals concerning secondary-task noise. For example, a simulator study paired a task-irrelevant email alert that participants must respond to vocally with a task-relevant auditory alert that indicated that they must press on the brakes immediately (Wiese & Lee, 2004). Their findings displayed that pairing the e-mail alert with the brake alert improved response time. The researchers postulated that these unexpected results were due to participants anticipating a brake event in case it were to arise while distracted by the email notification.

2.2 Aging and Auditory Alert Systems

With age, there is an overall decline in auditory processing and its mechanisms (Nagaraj et al., 2015). As reported by the World Health Organization (2018), 93% of all individuals with hearing impairments are adults, and one third of all those aged 65 and above are affected. Thus, the inhibitions and hearing impairments that come with age must be considered when designing auditory alerting systems. Maltz et al. (2004) conducted a study investigating how auditory alerting systems of varying reliability impact older and younger participants' performance on a driving task, as well as their response to said alerts. In addition to the driving task, one condition also played participants an audiobook to evaluate how divided auditory perception would impact their performance. Findings showed that generally, highly reliable alerting systems helped improve performance and response to alerts across both age groups. That said, the older group had a higher tendency to ignore or miss false alarms when distracted by the audiobook compared to the condition where they were not required to listen to the audiobook (Maltz et al., 2004). These results are in line with other literature that has found that in-vehicle auditory alerts help compensate for all forms of age effects and even prevent incidents in older adults (Baldwin et al., 2014; Marshall et al., 2014).

2.3 Neural Resource Allocation and Auditory Alerting Systems

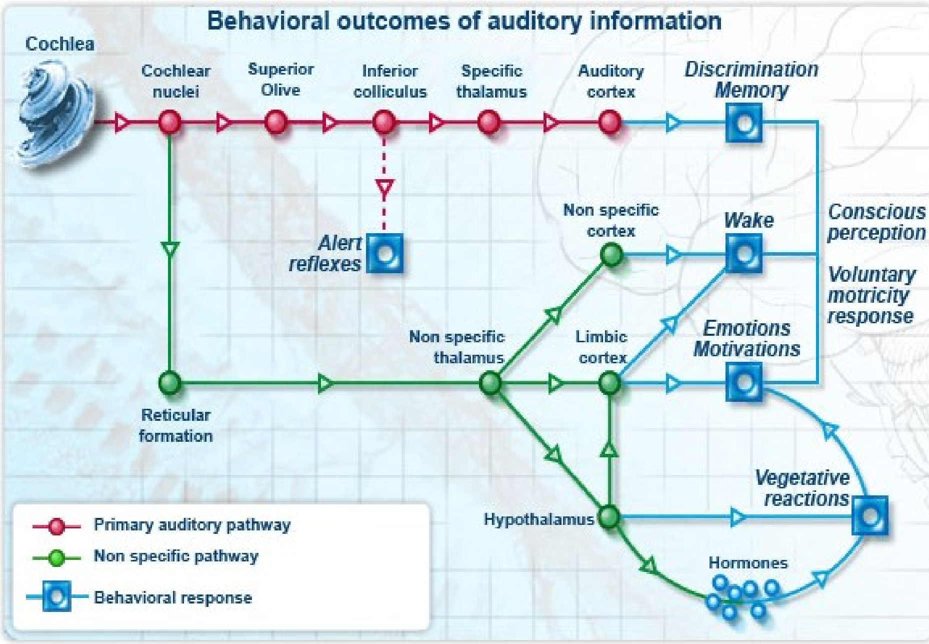
Regardless of its level of autonomy, driving a vehicle involves the perception of multiple modes of information and decision-making based on the available information. The ability to drive requires one of the main components of human cognition that permits humans to interact with their surroundings, known as working memory, where sensory information is processed, stored, and retrieved for use (Andrade, 2001). Working memory is constantly engaged and particularly important during driving tasks, mainly because there is a limit on how much the system can handle (Baddeley, 2003). Bustamante et al. (2007) attempted to understand how varying workload and alert threshold would impact human performance on a modified Multi-Attribute Task Battery. The threshold of auditory alerts had three levels; low, medium, and high. Low-threshold alerting systems were prone to false alarms, while high-threshold alerts risked missing instances where an alarm is necessary, thus impacting the reliability of the alarm systems. In general, they found that regardless of the threshold of the alerts, participants presented faster response times during the low-workload condition compared with the high-workload condition. In contrast, in the high-workload condition, improvements in response times were only seen in response to low-threshold alarms where the likelihood of false alarms was high. While humans are certainly limited in workload and processing of information, as the information available, or data, improves, the level of performance attainable also improves. The relationship between human performance on tasks and the information available is particularly promising when considering that one goal of semi-autonomous vehicles is to require as little human interaction as possible. That said, this relationship also highlights the importance of designing semi-autonomous vehicle safety features in a manner that takes into consideration age and workload.

2.4 Auditory Processing Pipeline

The auditory processing pipeline portrays the regions of the brain through which auditory information flows. As depicted in Figure 1 below, auditory information is first projected from the cochlea along the primary auditory pathway (the primary auditory cortex), and the non-specific pathway (which falls near the somatosensory association cortex), and from these areas is later projected to the behavioural response locations of the brain (which includes the dorsolateral prefrontal cortex) (Pujol, 2020). The functions associated with each of the regions of interest mentioned in the auditory processing pipeline will be discussed in the following sections.

Figure 1

The Auditory Processing Pipeline



Note. The auditory processing pipeline displayed above (Pujol, 2020) depicts the flow of auditory information through the three regions of interest; the primary auditory cortex to the somatosensory association cortex, and finally, the dorsolateral prefrontal cortex.

2.4.1 Primary Auditory Pathway: Primary Auditory Cortex

The primary auditory pathway or the "classical" auditory system includes the main site where auditory information is processed, the primary auditory cortex (Møller, 2006). The primary auditory cortex is the main site for processing auditory information, which includes perceiving auditory stimuli, interpreting pitch and sound intensity, auditory working memory involvement, as well as other auditory-related responsibilities (Trans Cranial Technologies, 2012).

2.4.2 Non-Specific Pathway: Somatosensory Association Cortex

In the non-specific pathway of auditory processing, information flows from the cochlea to the non-specific thalamus, where it is then projected to the somatosensory association cortex. This pathway is considered “non-classical” as it projects to regions other than the “classical” primary auditory regions (Møller, 2006). The somatosensory association cortex has several responsibilities, many unrelated to auditory processing. Still, those that pertain to this research most include processing sensory information (including auditory information) and keeping track of phonological relationships (Trans Cranial Technologies, 2012). Within the context of semi-autonomous vehicles, auditory information and its associated meaning are important as humans must be able to keep track of and identify different alerts as well as act on them.

2.4.3 Behavioural Response: Dorsolateral Prefrontal Cortex

The final region of interest, one portion of the behavioural response pathway, is the dorsolateral prefrontal cortex. The dorsolateral prefrontal cortex, and the frontal regions in general, receive inputs from both the classical and non-classical pathways (Osmanski & Wang, 2015). The dorsolateral prefrontal cortex region is involved in phonological processing, but it is also highly involved in executive function and working memory (Trans Cranial Technologies, 2012). Within the context of this study, it is important to keep in mind that this region will not only be involved in auditory processing but also the visual working memory task.

2.5 Neurophysiological Indicators of Aging

2.5.1 Sensory Gating

Sensory gating refers to the neural ability to filter out unimportant or redundant information (Freedman et al., 1987; Jones et al., 2016). It is a form of inhibition that limits the amount of information processing when stimuli are redundant (Frith, 1979), freeing up resources to process novel information. Sensory gating is one index of attention resource allocation that can be measured objectively and easily and is often done using a paired-click paradigm (refer to section 2.6 for more about the paired-click paradigm). Sensory gating is typically evaluated using neuroimaging, such as EEG. The neural phenomenon is visible in event-related potentials (ERPs) as the attenuated response to repetitive stimuli at key latencies, such that the first tone presented evokes a larger amplitude than the second (Lijffijt et al., 2009). Deficiencies in gating, particularly when associated with auditory processes, may signal individuals at risk due to inefficient cognitive processes.

2.5.2 Age-Related Neurophysiological Theories

As mentioned earlier, it is widely known that with age comes a decline in the neurological mechanisms involved in auditory processing. There are multiple theories surrounding age-related changes seen in neural processing, and some of which will serve as recurring themes throughout this document. The primary hypothesis that pertains to this research is the Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH) (Reuter-Lorenze & Cappell, 2008). The CRUNCH model suggests that older adults allocate more neural resources for lower workload tasks than would be seen in a younger brain. Another hypothesis is the Posterior-Anterior Shift in Aging (PASA), which is characterized by increased frontal (anterior) activity, and decreased occipital (posterior) activity that is often seen in older adults (Davis et al., 2007). The final age-related hypothesis mentioned is the Hemispheric Asymmetry Reduction in Older Adults (HAROLD) which presents bilateral prefrontal activity in older adults (Cabeza, 2002). Each of these theories of age-related changes in neural processing is similar in that the older brain seeks out alternative methods for task completion when it anticipates that neural resources in original pathways may not be sufficient. As such, age-related changes in neural processing should not necessarily be seen as a shortcoming.

2.6 Auditory Paired Tone Oddball Paradigm

The present study combines two experimental designs; the paired-click paradigm and the oddball paradigm. The auditory paired-click paradigm involves presenting identical auditory stimuli in quick succession of one another and is often used to evaluate sensory gating and determine if redundant information is being inhibited normally (Shen et al., 2020). In contrast, the auditory oddball paradigm presents several identical auditory tones and fewer non-identical tones (the infrequency of the deviant tone results in the brain identifying the stimulus as different or oddball) (Liebenthal et al., 2003). In the combined auditory paired-click oddball paradigm used in this study, two tones are presented sequentially, with deviant tones interspersed throughout the study in the second stimulus position. The second deviant tone was identical to the second standard tone in intensity and morphology, except that it was played at 1500 Hz rather than at 1000 Hz, which was the frequency of all the standard tones. The occurrence of deviant to standard tones was 1:13. In other words, less than 10% of the tones were deviant. This experimental design is novel and allows for the investigation of both sensory gating and how deviant information can overcome neural redundancies.

2.6.1 P200 Component

The component of interest in this research includes the P200, which is the positive-going amplitude that occurs approximately 200 milliseconds after the presentation of an auditory tone. The P200 component was chosen for this research because it represents later attentional processing (Boutros et al., 2004) and is suggested to also play a role in perceptual processing (Bourisly & Shuaib, 2018). The P200 is particularly appropriate for this research, given that responses to semi-autonomous vehicle auditory alert systems rely on attentional and perceptual processes. In a passive paired-click study put forth by Gmehlin et al. (2011), they evaluated the P200 component in addition to earlier latencies across older and younger participants who simultaneously completed various working memory tasks. They found that sensory gating was preserved in both age groups. However, there was an effect of age where the P200 component was not as effectively sensory gated in the older group. The findings suggest that the P200 component is responsive to individual differences, such as normal aging, which is a crucial aspect of auditory processing being evaluated in this study.

2.7 Present Research

This research used EEG to investigate how deviant auditory stimuli can be used to overcome sensory gating across visual memory workload levels and age groups. Specifically, neural ERP responses associated with sensory gating at the P200 latency will be examined. Evaluating these factors will help to understand how auditory alert systems in semi-autonomous vehicles can be optimized to ensure safety. The first two hypotheses relate to the validation of the study design.

1. It is predicted that at the somatosensory association cortex, the second standard redundant tone will demonstrate smaller P200 components as compared to the first standard tone (refer to Figure 2).

2. It is predicted that at the somatosensory association cortex, the deviant second tone will result in larger P200 components as compared to the second standard tone (refer to Figure 2).

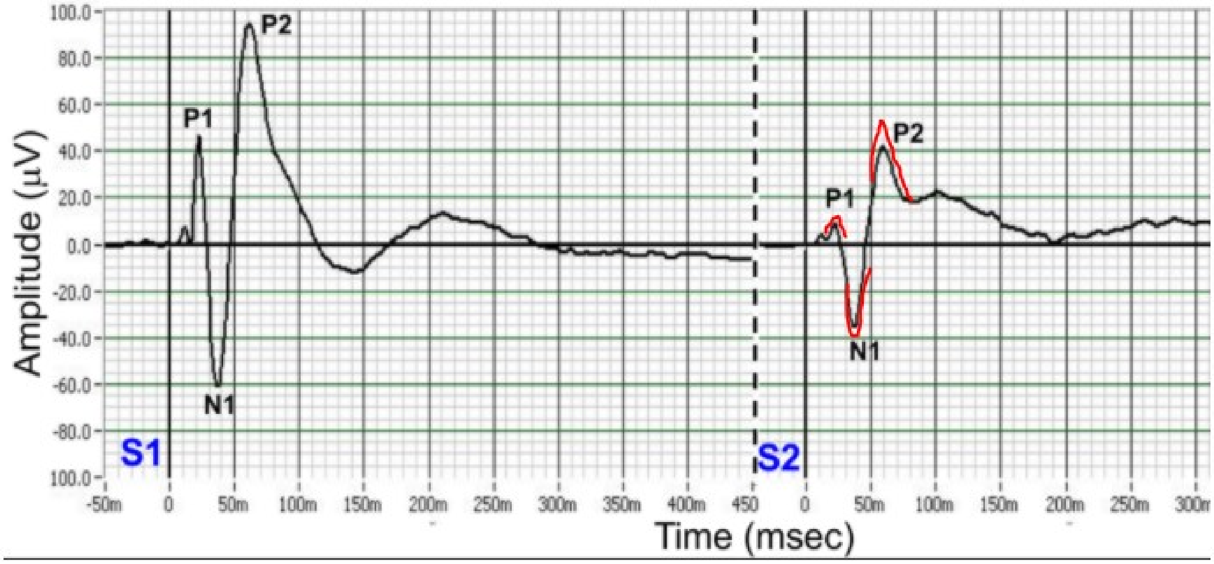
The remaining hypotheses relate to the impact of deviant auditory stimuli on sensory gating at three key auditory processing cortical regions (primary auditory cortex, somatosensory association cortex, and dorsolateral prefrontal cortex).

3. It is hypothesized that there will be no effect of Age on the P200 response for the deviant second tone in the low-workload condition.
4. As per the CRUNCH theory (Reuter-Lorenze & Cappell, 2008), it is hypothesized that there will be a reduced effect of deviance on P200 component responses in the older group compared to the younger group in the high-workload condition.

This study allows us to investigate the effects of older age in critical semi-autonomous vehicle high-workload handover situations where there is a high probability of auditory stimuli being redundant.

Figure 2

Example ERPs in response to the First Standard Tone and the Second Standard Tone The Auditory Processing Pipeline



Note. Figure obtained from Ahnaou et al. (2016). S1 = first standard tone and S2 = second standard tone. The second stimulus is presented 500 ms after the presentation of the first stimulus. The red overlay for the second tone is a predicted increase in neural response to the frequency difference of the second deviant tone (which occurs less than 10% frequency of the second standard tone).

Chapter 3: Methodology

3.1 Participants

This study consisted of 28 participants (16 female) divided into two groups, younger and older. The younger group was made up of undergraduate Psychology students at Carleton University (n = 17, M = 19.24, range = 18 – 26), while the older group were obtained from the same institutions "learning in retirement" program (n = 11, M = 68.82, range = 57 – 78). Compensation included a 2% course credit for the younger group and for the older group free refreshments valued at $20.00. The inclusion criteria for the older participant group included individuals above the age of 50, who had normal hearing and were English speakers. This study received ethics clearance from Carleton University's Research Ethics Board (Project number 104917, see Appendix A).

3.2 Procedure

3.2.1 Introduction and Pretest Questionnaire

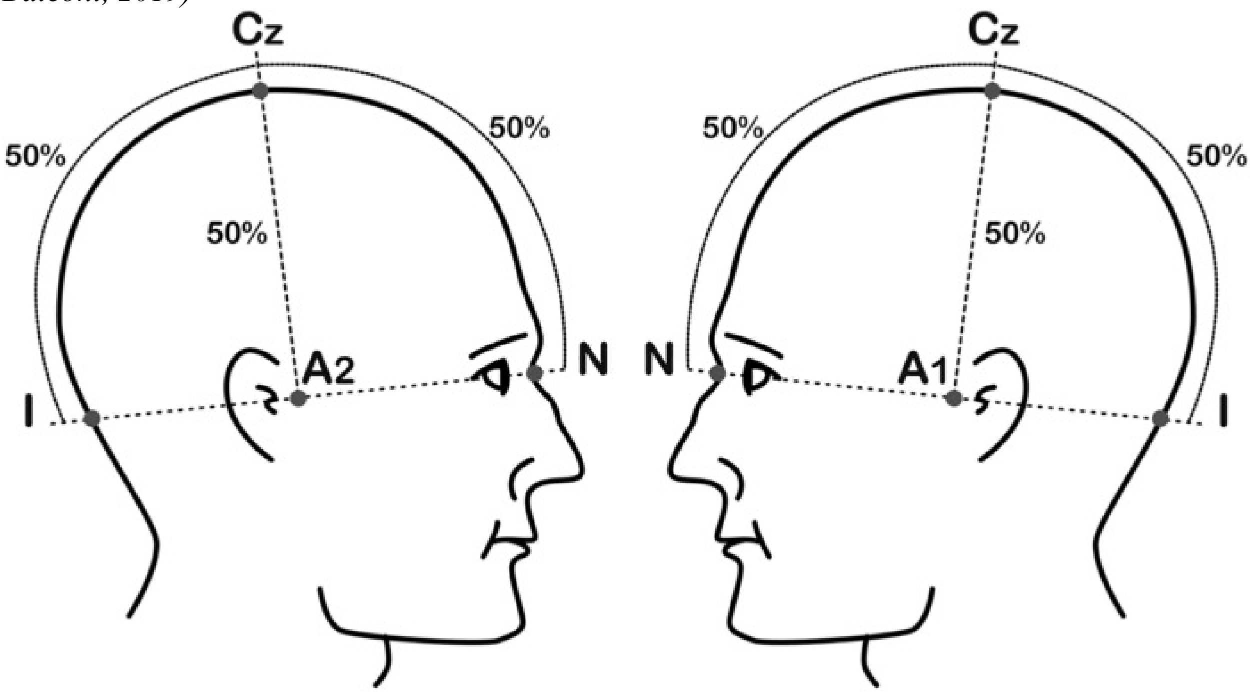
Upon arrival, participants were familiarized with the events of the study. After providing informed consent, they were given a pre-test questionnaire to fill out (see Appendix D), which requested information about the participants' state and any relevant health conditions or medical history that would impact the neural or behavioural data.

3.2.2 EEG Procedures

Once participants arrived, the EEG headset was immersed in a solution of distilled water, potassium chloride, and baby shampoo to provide a medium for scalp electrical activity. To ensure that the electrode net was correctly placed on the scalp, measurements were taken to locate the vertex of the participant's head (see Figure 3). Once the Vertex location was obtained, the headset was placed, parting the hair as needed to obtain direct skin placement, and adjusted as needed.

Figure 3

Diagram of the Vertex (Cz) Inion (I) Nasion (N) and Preauricular Point (A1/A2) (Carlstedt & Balconi, 2019)



Note. Cz = vertex, I = inion, N = nasion, and A1/A2 = preauricular point. Image obtained from Carlstedt & Balconi (2019).

3.2.3 Auditory Tones for Modified Oddball Paradigm

Once set up with the EEG headset, participants sat in front of an LCD monitor, where they were also equipped with over-ear headphones and a response pad (Figure 4). Throughout the experiment, they wore the headphones which delivered paired tones using a modified paired tone and oddball protocol (1000 Hz and 1500 Hz [deviant]). This design examined whether redundant stimuli could be re-assigned attention if they became more salient. The tone pairs consisted of a standard-standard pair and a standard-deviant pair. The inter-tone interval between paired tones was 500 ms. Tone pairs were delivered every 4 to 7 seconds. The first three pairs of tones in a block were always standard-standard tones to maximize the oddball effect. After a standard-deviant pair of tones, the next two pairs of tones were always standard-standard pairs. The deviant tone occurred approximately 10 percent of the time. Participants were instructed that these tones were passive in nature and that they did not need to act on them or pay attention to them.

Before beginning the visual memory task, participants were shown a 5-minute video of nature scenes to obtain a baseline of neural activity (not analyzed in the present analysis). Participants were requested to move as little as possible throughout testing to reduce movement artifacts in the recorded EEG.

3.2.4 Audiometry Procedures

The tone frequencies (set at 1000 Hz [standard] and 1500 Hz [deviant]) were selected as they fall within the normal hearing threshold for older adults, which lies between no more than 0 and -25 decibels of hearing loss (Shnupp et al., n.d.). To account for the natural loss of hearing in the older participant group, and potential hearing impairments of younger participants, several auditory acuity tests were in place to ensure that participants detected the tones. Upon arrival, participants had to self-report normal hearing to continue the study. In the context of this research, normal hearing referred to an individual who is not medically diagnosed as hearing impaired. In addition to having self-reported normal hearing, participants were asked at several points whether they could hear the tones. The intensity of the tones remained the same for each participant, so as to not inadvertently introduce differences in the neural activity. Finally, the ERP method required that participants showed stereotypical brain responses to the tones, such as the N100 and P200 deflections after the tone onset. Only participants with the stereotypical tone responses were used in the present analyses (see section 4.1 for the audiometry analysis).

3.2.5 Visual Memory Task

After watching a 5-minute video of nature scenes to obtain a baseline, participants completed a visual memory task (Figure 4). The visual memory task involved presenting a series of two checkerboard pattern grids, sequentially, on an 18-inch LCD monitor. Participants determined whether the second grid matched the first grid. Responses, "same" or "different", were recorded using button presses on a response pad with their preferred hand (Figure 4). The visual stimuli were generated and presented using a custom Python 2.7 script. Participants completed four blocks of the visual memory task with two alternating workload levels, low and high, encountering each workload level twice. The workload level was based on the number of cells present in the grid and the number of filled-in cells. In the low-workload condition, the grid was composed of 25 cells (5 by 5), with two cells filled. In the high-workload condition, the grid consisted of 49 cells (7 by 7), with 7 cells filled. In the "different" conditions, only one of the blocks would move, regardless of the workload level. Workload order was counterbalanced across participants. Response times and accuracy on the visual memory task were obtained as behavioural measures.

Figure 4

Study Materials and Equipment

Note. Left: Geodesic sensor net with headphones. Middle: Response pad, monitor, and headphones. Right: Stimuli for the visual memory task (top cells were low-workload and bottom cells were high-workload) (Turabian et al., 2020).

3.2.6 Debriefing

After completing all blocks of the visual memory task, the EEG headset was removed, and participants were debriefed on the purpose of the study. Participants were allowed to finish their refreshments and ask questions to the researcher.

3.3 Study Design

Data from the visual memory task were analyzed using a 2 x 2 factorial ANOVA, comparing Workload (low vs. high) and Age (younger vs. older). The EEG analysis implemented a 2 x 2 x 2 factorial ANOVA, with Stimulus Position (first vs. second), Tone Type (standard vs. deviant), and Age (younger vs. older) as the factors. The significance threshold for each analysis was set at $p < .1$. The order of the workload conditions was counterbalanced to account for order effects. Baseline EEG was obtained by having participants passively watch a five-minute nature video, which always occurred before the visual memory task. The EEG from the baseline condition was not analyzed in the present work.

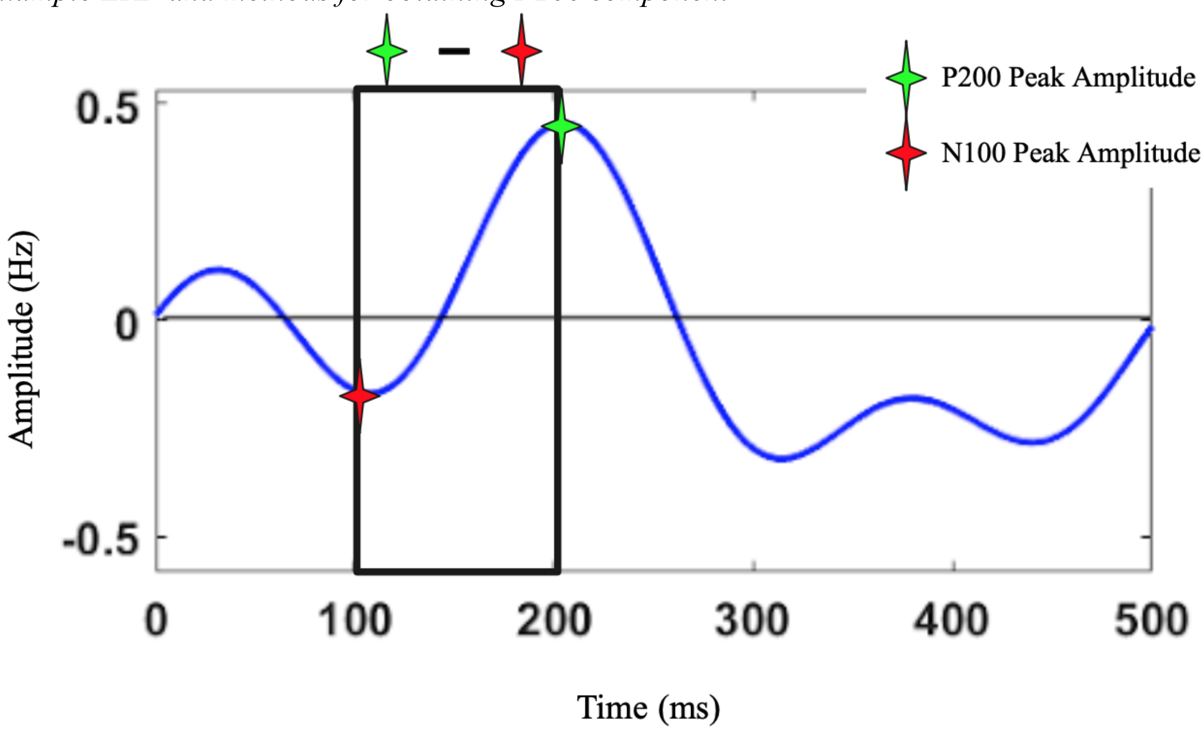
3.4 EEG Pre-Processing and Evoked Potentials

EEG was recorded at 1000 Hz using a 128-channel dense array system and a GES 250 amplifier. To record and reduce the data to 250 Hz, the software Net Station 4.3.1 (Electrical Geodesics, Inc.) was used. Data were processed, and artifacts were removed (as described below) using EEGLAB v.14 (Delorme & Makeig, 2004). The same software was used to extract EEG amplitudes at pre-determined latencies and create ERPs for each condition. Data were filtered offline with a 1 to 30 bandpass, and to further identify and remove non-brain artifacts (such as muscle movements, eye blinks, and cardiac induced activity), an independent component analysis was used. Triggers were inserted into the recording by the stimulus presentation software at the onset of each tone. Epochs had a baseline of 100 ms and extended for 500 ms post-stimulus. The Study function in EEGLAB computed grand averages of the epochs at each electrode for older and younger groups.

The latency of interest in this research was 200 milliseconds after the onset of the tone, known as the P200. To obtain the relative deflection of the P200 value, the peak negative-going deflection of the N100 and peak positive-going deflection of the P200 was extracted. The absolute difference between the negative and positive deflection associated with the P200 was calculated to obtain the P200 measurement associated with each tone stimulus (μV) (see Figure 5).

Figure 5

Example ERP and methods for obtaining P200 component

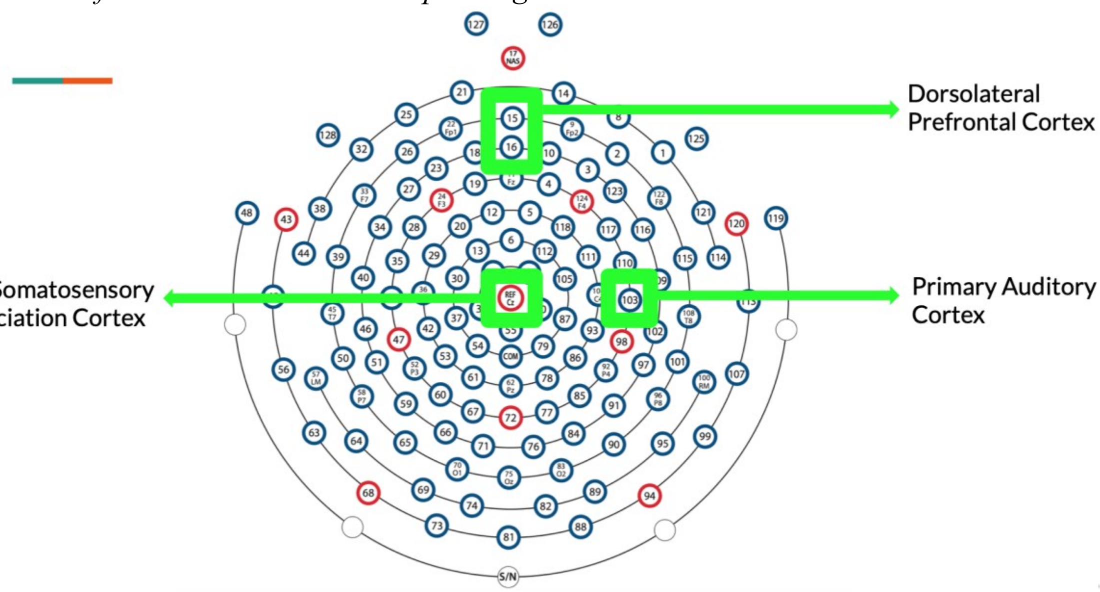


3.4.1 Brain Regions of Interest

The brain areas of interest represent key regions on the auditory processing pipeline discussed in earlier sections. The first area of the brain evaluated includes the primary auditory cortex, which falls under electrode 103. The next area of the brain is the somatosensory association cortex, associated with the Cz electrode. The final region of interest includes the dorsolateral prefrontal cortex, associated with electrodes 15 and 16. The values from the 15 and 16 electrodes were averaged. See Figures 6 and 7 for visual representations of the regions of interest both on the EEG headset and anatomically.

Figure 6

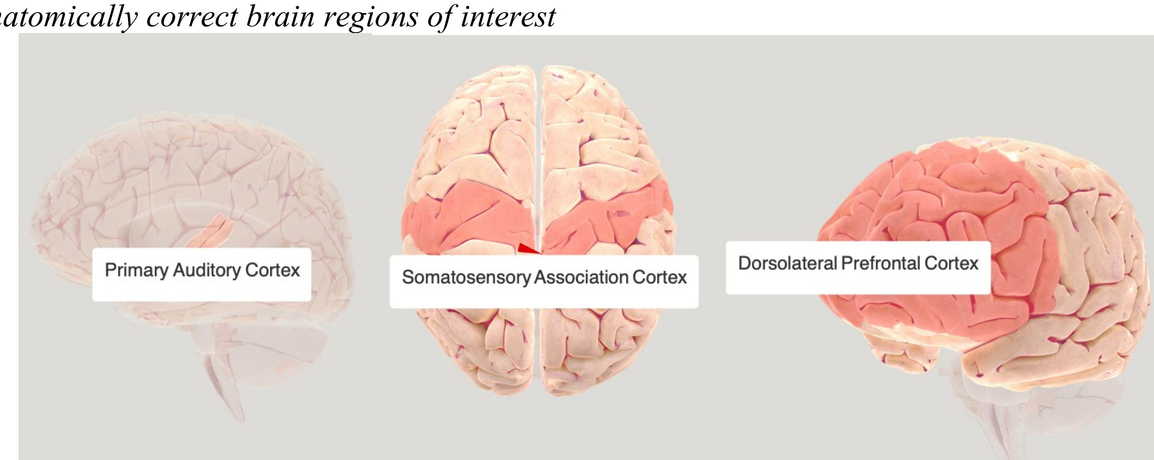
Brain areas of interest and their corresponding electrodes



Note. Image of EEG 128 Channel Dense Array Headset obtained from Magstim EGI (n.d.).

Figure 7

Anatomically correct brain regions of interest



Note. Image obtained from the Society for Neuroscience (2021).

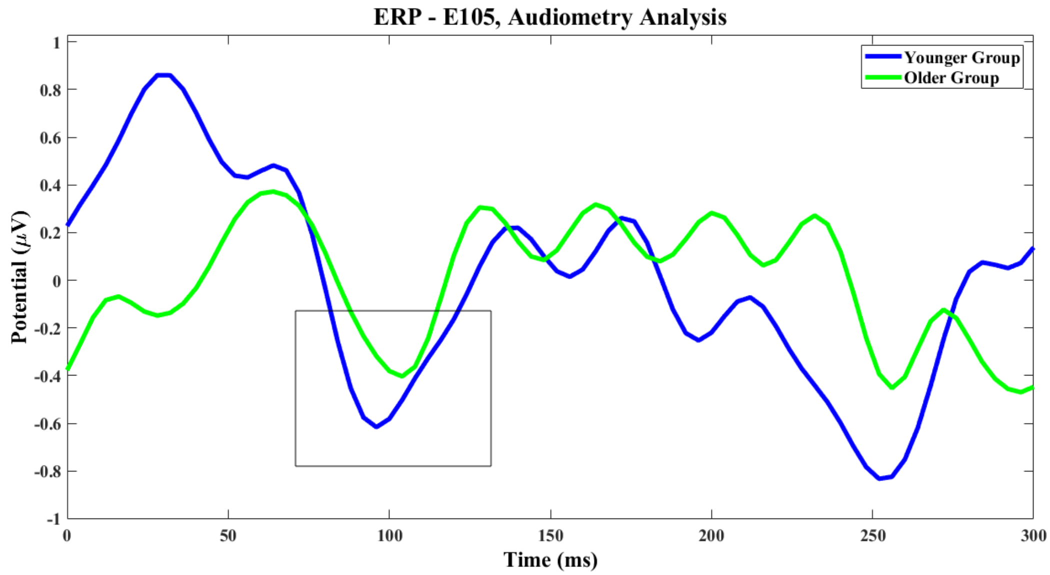
Chapter 4: Results

4.1 Audiometry Analysis

Participants were delivered paired tones through headphones using a modified oddball protocol, with the standard tones set at 1000 Hz and the deviant tones at 1500 Hz. Approximately 10% of the tones were deviant. The 1000 and 1500 Hz pure tone frequencies fall within the normal hearing threshold for participants in the older age group in the present study, which falls between no more than 0 and -25 decibels of hearing loss (Schnupp et al., n.d.). As the detection of higher frequencies is typically lost first in older age, it was important to manage this potential age-related hearing loss confound. All participants had normal self-reported hearing function. No clinical audiometry screening was performed. In addition to self-report data and selecting a sound frequency that considers the natural hearing loss that occurs with age, participants were asked to verify that the tones were clear and at an appropriate volume throughout the experiment. The final analysis that was conducted to ensure that the tones were being processed was the evaluation of the N100 ERP (associated with stimulus feature detection) in both age groups. It was expected that the N100 would be similar for older and younger participants. As seen in Figure 8 below, the N100 component for both the older and younger group is similar, indicating that the tones are being processed as expected.

Figure 8

ERP Audiometry Analysis of the N100 component



Note. The N100 presents activity 100 ms post-onset of the auditory stimulus. The above figure shows no significant differences between age groups.

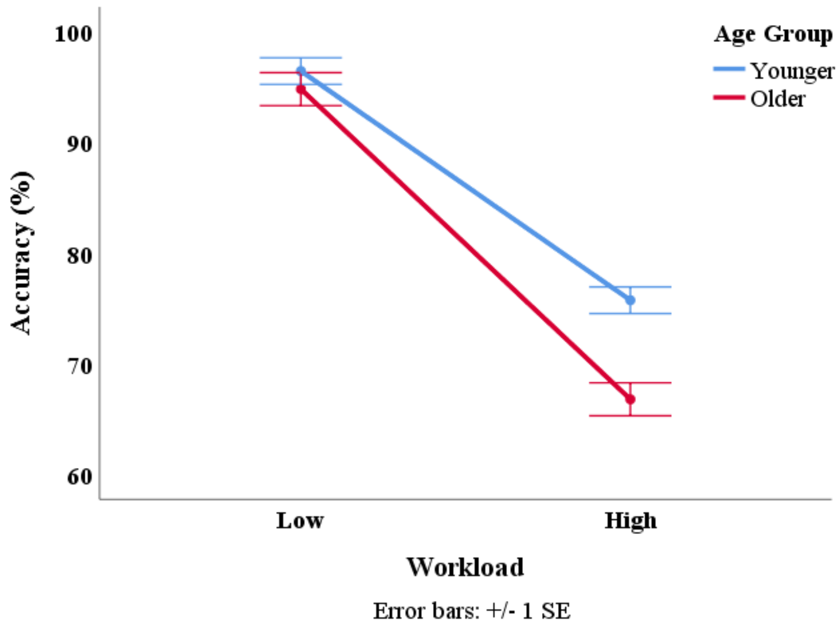
4.2 Behavioural Measures

4.2.1 Accuracy Rating

As shown in Figure 9, a main effect of Age on accuracy was found, such that the older group displayed lower accuracy (M = 80.80, SD = 15.75) than the younger group (M = 86.09, SD = 12.53), F(1, 108) = 15.26, $p < 0.001$, $\eta_p^2 = 0.12$. There was also a main effect of Workload where the high-workload condition (M = 72.23, SD = 9.91) resulted in lower accuracy than the low-workload condition (M = 95.79, SD = 4.24), F(1, 108) = 323.45, $p < 0.001$, $\eta_p^2 = 0.75$. There was also a significant interaction between Workload and Age, whereby the negative effect of Age on accuracy was observed only in the high-workload condition (younger group: M = 75.74, SD = 8.85; older group: M = 66.80, SD = 9.13), F(1, 108) = 7.29, $p = 0.01$, $\eta_p^2 = 0.06$.

Figure 9

Mean Accuracy Percent by Workload by Age

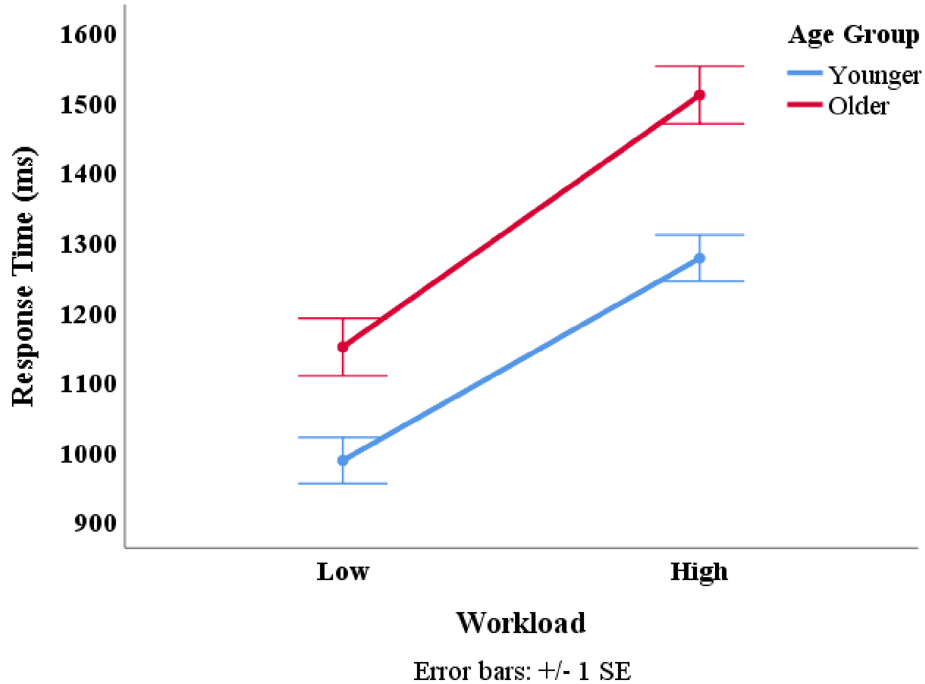


4.2.2 Response Time

As shown in Figure 10, a main effect of Age was found, such that the older group displayed longer response times (*M* = 1329.07, *SD* = 259.04) than the younger group (*M* = 1131.06, *SD* = 244.50), $F(1, 108) = 28.03$, $p < 0.001$, $\eta_p^2 = 0.21$. There was also a main effect of Workload, where mean response times in the high-workload condition (*M* = 1367.56, *SD* = 218.97) were longer than in the low-workload condition (*M* = 1050.13, *SD* = 212.33), $F(1, 108) = 75.54$, $p < 0.001$, $\eta_p^2 = 0.41$.

Figure 10

Mean Response Time (ms) by Workload by Age



4.3 EEG Results

For the EEG analyses, after filtering the data and determining the number of clean datasets (refer to section 3.4 for cleaning processes), the participant group was reduced to 10 participants (7 female) split into younger (*n* = 5, M = 19.6, range = 18 – 21) and older groups (*n* = 5, M = 70.8, range = 65 – 78). This number of participants was reached because out of the original sample, only 5 older participants, and 10 younger participants had usable EEG data. To match the participant groups, 5 participants from the usable data of the younger group were chosen at random to ensure no bias.

The following sections present the extracted P200 values (in µV) from ERPs at different locations of the brain (primary auditory cortex, somatosensory association cortex, and dorsolateral prefrontal cortex) within different Workloads (low and high), Tone Types (standard and deviant), and Age groups (older and younger adults). The EEG analyses implemented a 3-factor mixed-design ANOVA, with Age as a between-subjects factor and Tone Type and Workload as within-subjects factors. The criteria for statistical significance was determined by setting both a p-value threshold ≤ 0.1 and an effect size threshold ≥ 0.1, where the effect size ranges were as follows: small 0.01 - 0.12, medium 0.13 - 0.25, and large > 0.26 (Cohen, 1988). Pairwise comparisons were conducted using Bonferroni post-hoc analyses. Error bars were set to ±1 standard error of the mean (SEM). Finally, extreme outliers identified in SPSS were winsorized, such that amplitude values were replaced by the next closest non-outlier (Hoffman et al., 2008).

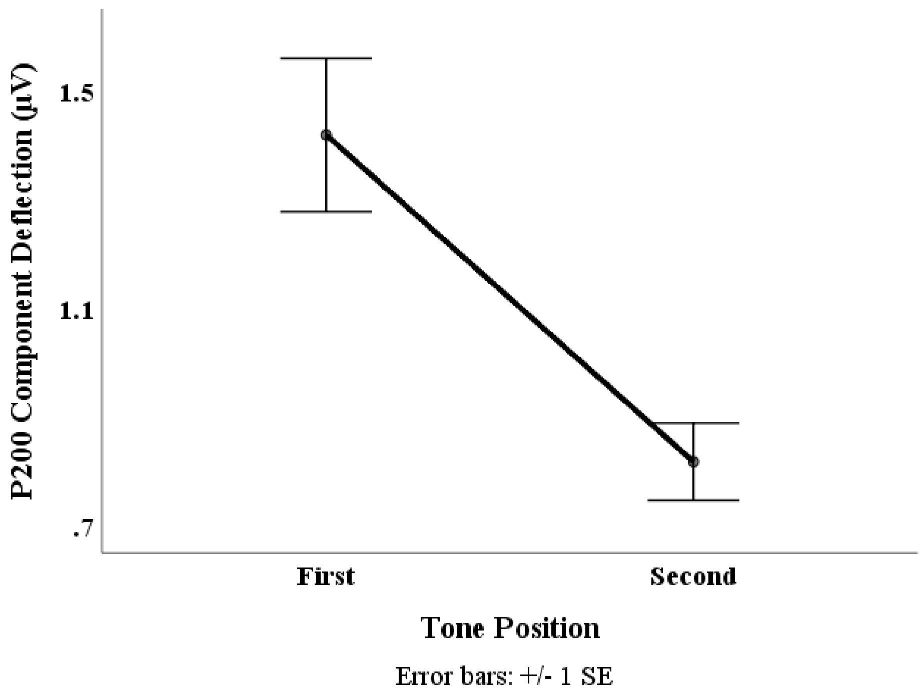
4.3.1 Paired Tone Paradigm Validation

The present study relied on the successful implementation of the paired tone paradigm to evaluate the brain's response to redundant, easily ignored stimuli. A repeated-measures ANOVA with two within-subject factors (Stimulus Position and Workload) and a single between-group factor (Age) was conducted for P200 amplitudes of standard tones at the somatosensory association cortex.

As shown in Figure 11, a large main effect of Stimulus Position (first or second click) on P200 components was found, such that the second tone (M = .82, SD = .29) was associated with smaller P200 deflections, as compared to the first tone (M=1.42, SD = .52), F(1,8) = 31.16, p = .001, η_p^2 = .79. No significant interaction between Age group and Workload with Stimulus Position was found, thus validating the paired-click research design in the present study.

Figure 11

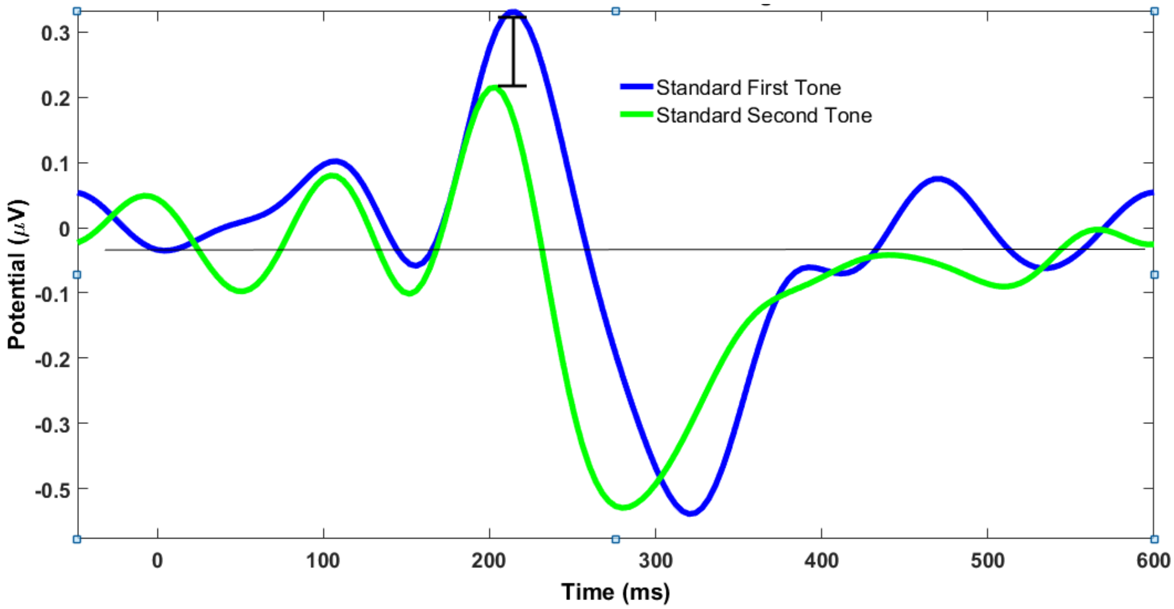
Analysis of P200 components based on Stimulus Position



Additionally, Figure 12 visually illustrates the reduction in the P200 component for the second tone. It is clear that the standard first tone resulted in a larger P200 component than the second tone.

Figure 12

ERP displaying the difference in P200 components upon the presentation of the first and second standard tone

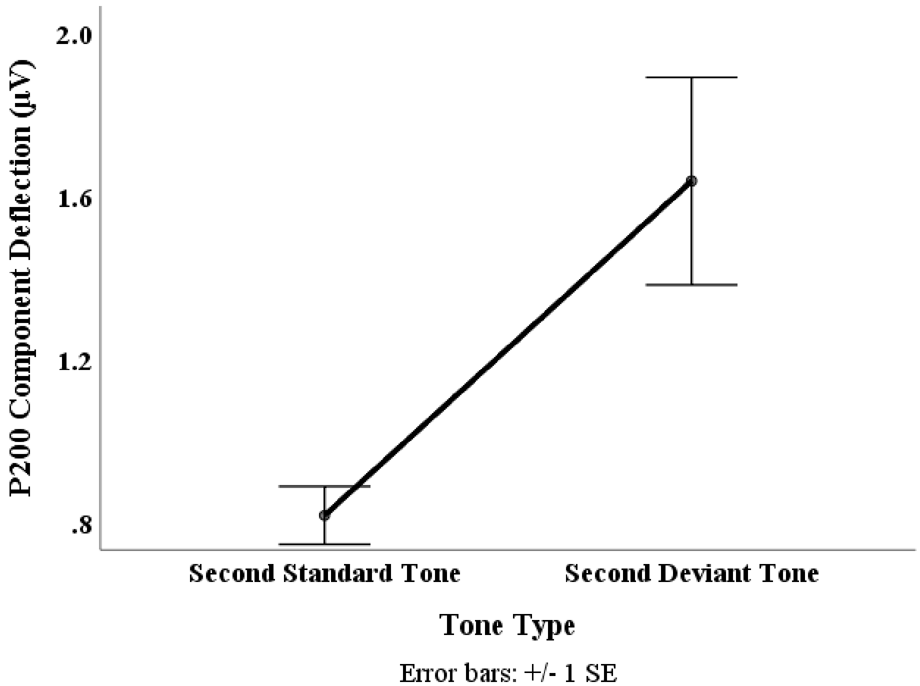


4.3.2 Oddball Paradigm Validation

The present study also relied on the successful implementation of the auditory oddball paradigm to evaluate the brain's response to redundant but salient stimuli. A comparison of the oddball and standard tones in the second position (500 ms after the first standard tone) was used to validate the oddball paradigm. As shown in Figure 13, a large main effect of Tone Type on P200 component amplitudes was found, such that the deviant tones ($M = 1.64$, $SD = .98$) resulted in larger P200 component amplitudes than the standard tones ($M = .82$, $SD = .29$), $F(1,8) = 12.30$, $p = .008$, $\eta_p^2 = .61$.

Figure 13

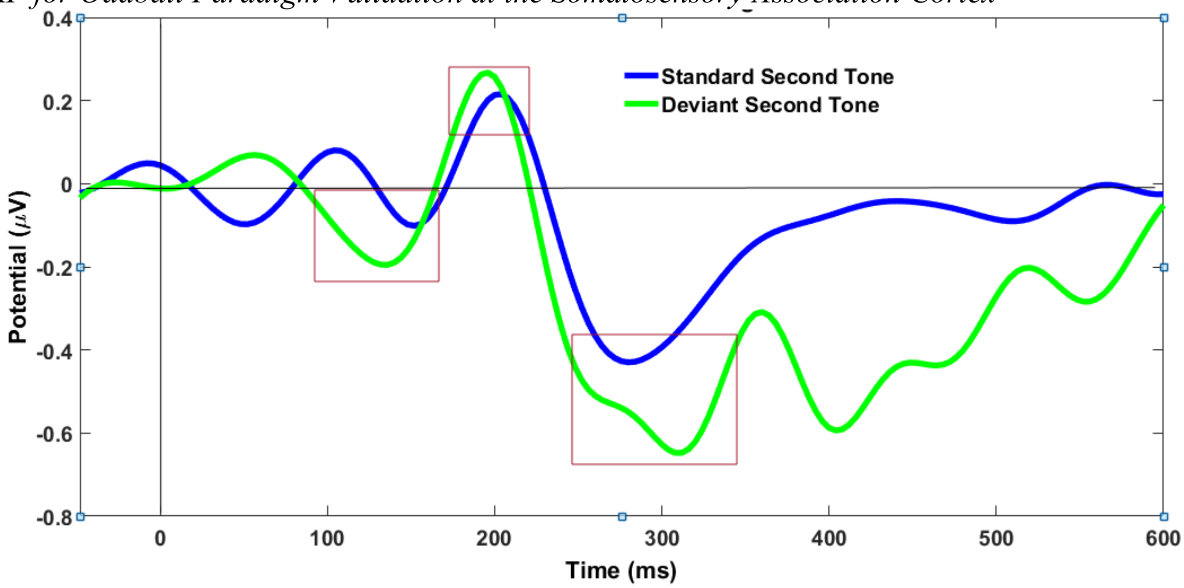
P200 amplitudes for the standard and deviant second tones at the somatosensory association cortex



In addition to the repeated measures ANOVA, the following figure visually presents the difference between the ERPs elicited by the standard second tone and the deviant second tone. Figure 14 illustrates the difference in P200 components for the standard and deviant second tones (combined age groups and workload conditions). Attenuation of the ERP elicited by the second standard tone is clear at the N100, P200 and N300 components.

Figure 14

ERP for Oddball Paradigm Validation at the Somatosensory Association Cortex



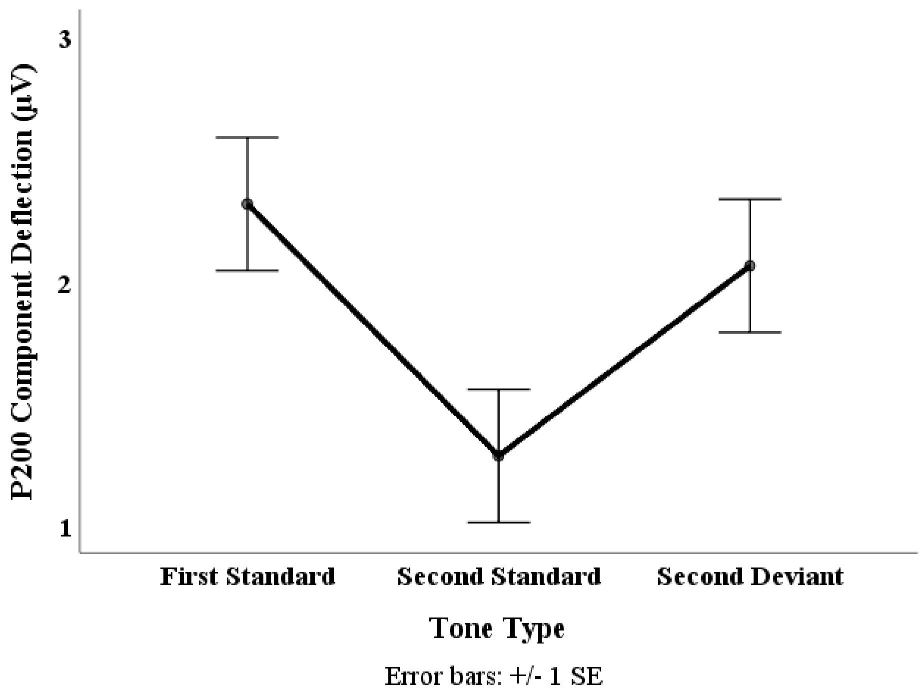
4.3.3 Overcoming Neural Redundancy (Sensory Gating) with Deviant Tones

To determine whether increased saliency of the second of the paired-click tones could overcome redundancy across both Age groups and Workload conditions, a series of repeated measures ANOVAs were conducted. The ANOVAs evaluated P200 amplitude differences across three Tone Types (first standard, second standard, and second deviant) and in two visual memory Workload conditions (low and high). Age was used as a between-group factor to confirm that the effect of increased salience for the second (deviant) tone was observed for both age groups.

4.3.3.1 Primary Auditory Cortex. There was no main effect of Age or Workload in the primary auditory cortex, $p > .1$. As displayed in Figure 15, there was a medium significant main effect of Tone Type on P200 component amplitudes, $F(2, 24) = 3.89$, $p = .035$, $\eta_p^2 = .25$. Post hoc analyses showed that the first standard tone ($M = 2.32$, $SD = .29$) and resulted in larger amplitudes than the second standard tone ($M = 1.29$, $SD = .59$), $p = .04$. The second deviant tone ($M = 2.06$, $SD = .87$) also resulted in larger amplitudes than the second standard tone, although this difference was not significant ($M = 1.29$, $SD = .59$), $p = .16$.

Figure 15

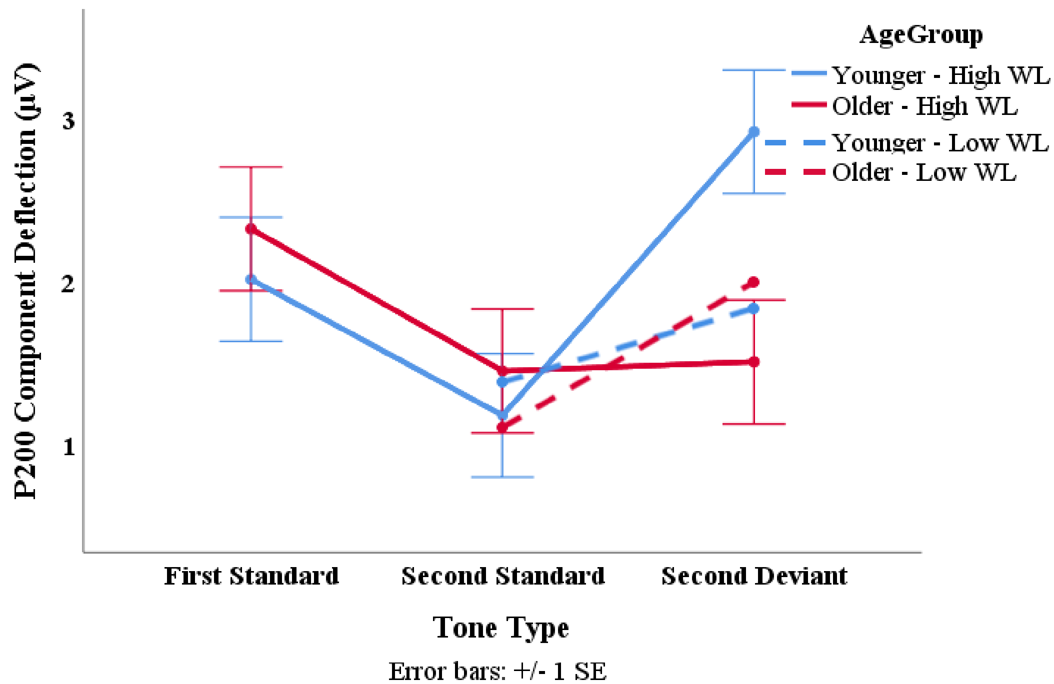
P200 Components elicited by the different Tone Types at the Primary Auditory Cortex



There was a 3-way interaction of a medium effect size between Age, Workload, and Tone Type on P200 component amplitudes, $F(1, 24) = 3.74$, $p = .039$, $\eta_p^2 = .24$. As presented in Figure 16, the effect of Age was only seen in the high-workload task upon the presentation of the second deviant tone, where the younger group presented larger P200 components (*M* = 2.91, *SD* = 1.20) than the older group (*M* = 1.50, *SD* = .47), *p* = .015.

Figure 16

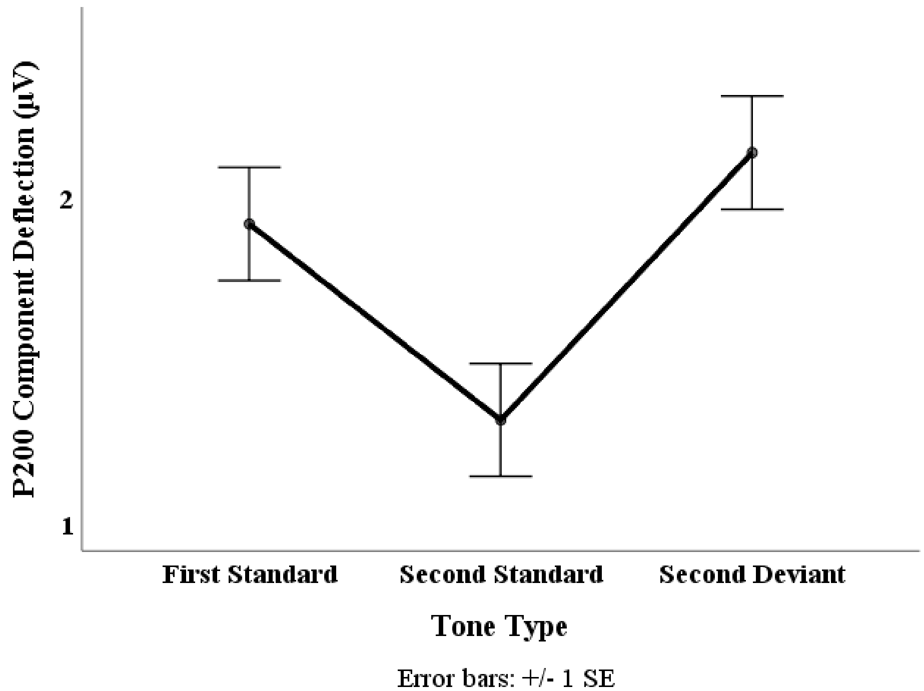
P200 Components elicited by the different Tone Types separated by Age in the high-Workload condition at the Primary Auditory Cortex



4.3.3.2 Somatosensory Association Cortex. As displayed in Figure 17, there was a large significant main effect of Tone Type on P200 component amplitudes, F(1, 24) = 6.02, p = .008, η_p^2 = .334. Post hoc analyses showed that the first standard tone (M = 1.42, SD = .51) resulted in significantly larger amplitudes than the second standard tone (M = .82, SD = .29), p = .07. Similarly, the second deviant tone (M = 1.64, SD = 1.07) also presented larger amplitudes than the second standard tone (M = .82, SD = .29), p = .008.

Figure 17

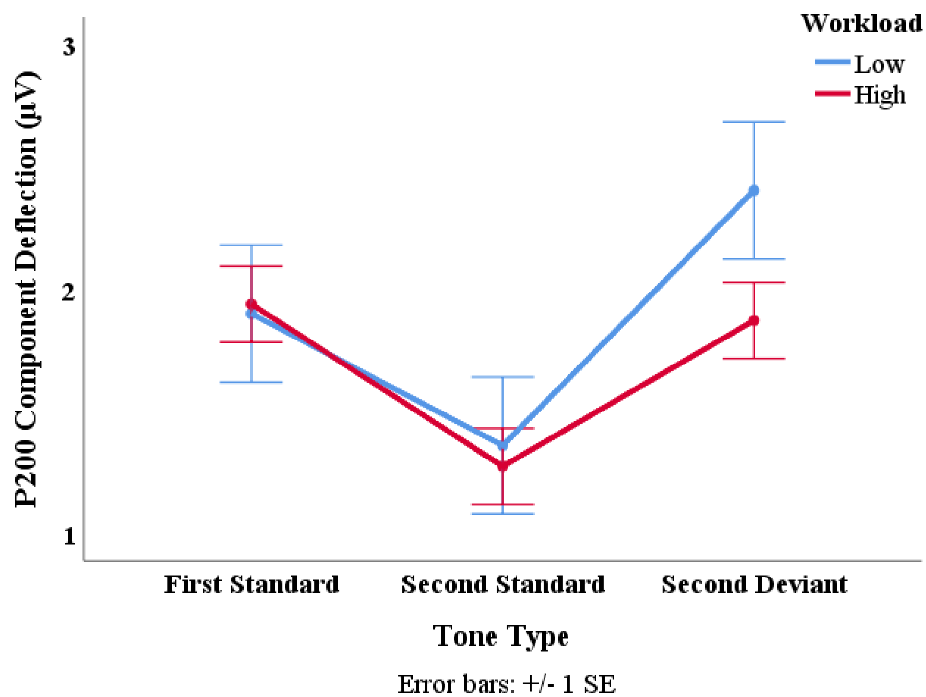
P200 Components elicited by the different Tone Types at the Somatosensory Association Cortex



There was no main effect of Age or Workload on P200 amplitudes at the somatosensory cortex. There was a marginal interaction with a small effect size between Tone Type and Workload on P200 component amplitudes, whereby the effect of Workload on P200 activity was only observed on the second deviant tone. The second deviant tone resulted in P200 components that were smaller in the high-workload task (M = 1.37, SD = .56) than the low-workload task (M = 1.90, SD = 1.40), $F(1, 24) = 3.30$, $p = .08$, $\eta_p^2 = .12$ (see Figure 18).

Figure 18

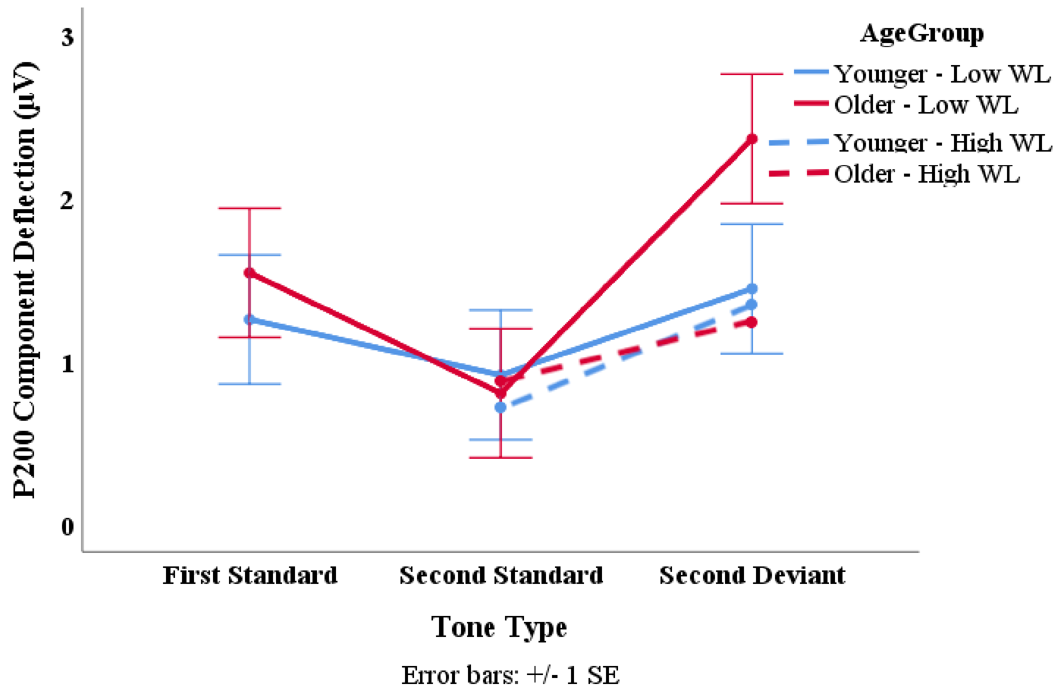
P200 Components elicited by the different Tone Types separated by Workload at the Somatosensory Association Cortex



Finally, a marginal 3-way interaction with a small effect size between Age, Tone Type, and Workload on P200 component amplitudes was found, as presented in Figure 19. The effect of Age on neural activity was only seen in the low-workload task upon the presentation of the second deviant tone, where the younger group presented more attenuation (M = 1.44, SD = .45) than the older group (M = 2.36, SD = 1.92), $F(1, 24) = 2.69$, $p = .11$, $\eta_p^2 = .10$.

Figure 19

P200 Components elicited by the different Tone Types in the low-Workload task separated by Age at the Somatosensory Association Cortex



4.3.3.3 Dorsolateral Prefrontal Cortex. There were no main effects of Tone Type, Age, or Workload in the dorsolateral prefrontal cortex, $p > .1$. There was a significant medium-sized interaction effect between Workload and Age on P200 component amplitudes, $F(1, 24) = 6.32$, $p = .019$, $\eta_p^2 = .21$. As shown in Figure 20, in the low-workload condition older age resulted in higher amplitudes (M = 2.72, SD = 2.52) as compared to the younger participants (M = 1.99, SD = 1.14). Whereas, in the high-workload condition, there was a reverse effect whereby there were attenuated neural responses among the older group (M = 1.79, SD = 1.09) as compared to the younger group (M = 2.60, SD = .97). Pairwise comparisons showed that the effect of Age was only seen in the high-workload condition (p = .018). There was no 3-way interaction between Tone Type, Age and Workload.

Figure 20

Interaction between Workload and Age group at the Dorsolateral Prefrontal Cortex

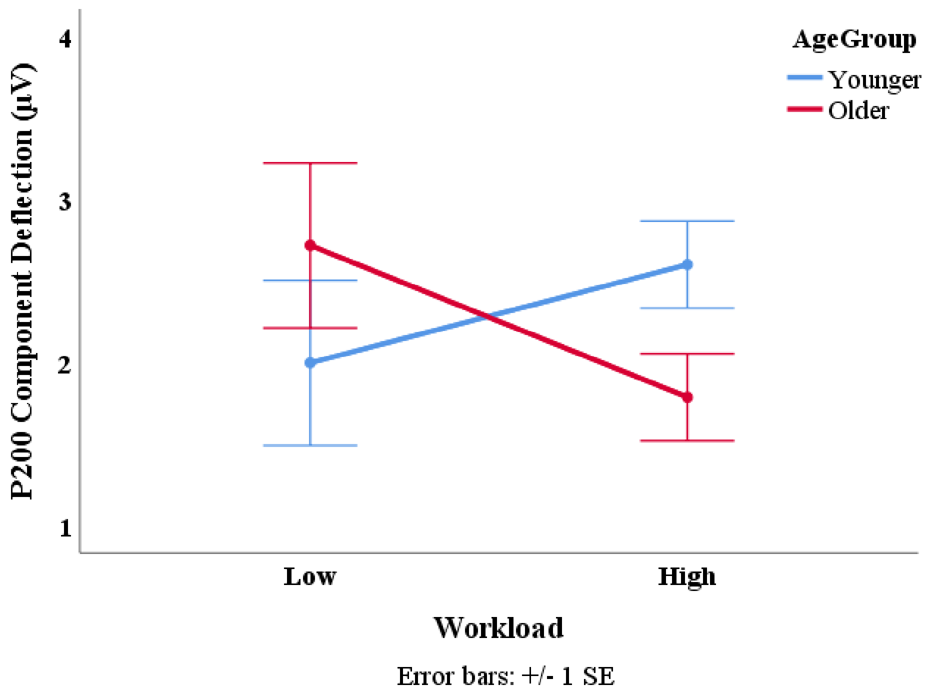


Table 1.

Summary of EEG Results

	Overcoming Neural Redundancy Using Deviant Tones
Primary Auditory Cortex The main region of the brain responsible for auditory processing.	Medium main effect of Tone Type on P200 component amplitudes where the first standard tone and second deviant tone resulted in larger amplitudes than the second standard tone. 3-way interaction of medium effect size between Age, Workload, and Tone Type on P200 component amplitudes, where the effect of Age was only seen in the high-workload task upon the presentation of the second deviant tone, where the younger group presented larger P200 components than the older group. **Regarding the safety of older drivers in high-workload conditions, evidence from the primary auditory cortex shows that the older adults did not overcome sensory gating as well as younger adults.**
Somatosensory Association Cortex Involved in processing phonological relationships.	Large main effect of Tone Type on P200 component amplitudes where the first standard tone and second deviant tones resulted in significantly larger amplitudes than the second standard tone. Marginal interaction between Tone Type and Workload (small effect size) where the effect of Workload on P200 component amplitudes was only observed on the second deviant tone. The second deviant tone had smaller P200 components in the high-workload task compared to the low-workload task. Marginal 3-way interaction (small effect size) between Age, Tone Type, and Workload on P200 components, where the younger group presented more attenuation than the older group in the low-workload task upon the presentation of the second deviant tone. This positive effect of older age in the low-workload condition was eliminated in the high-workload condition. **Regarding the safety of older drivers in low-workload conditions, evidence from the somatosensory association cortex shows that younger adults did not overcome sensory gating as well as older adults.**
Dorsolateral Prefrontal Cortex Involved in phonological processing and executive function.	Significant interaction of medium effect size between Workload and Age on P200 component amplitudes, where the effect of Age is only present in the high-workload condition, whereby the older group presented more attenuation than the younger group. **Regarding the safety of older drivers, evidence from the dorsolateral prefrontal cortex shows that older adults did not overcome gating in high-workload conditions compared to younger adults.**

Chapter 5: Discussion

This research aimed to investigate how the brain processed redundant auditory tones during visual tasks and how older age and higher levels of workload influenced this processing. A novel paired-click auditory oddball paradigm was used to investigate whether redundancy of tones was equally overcome in older and younger groups by increasing the salience of the normally redundant tones.

5.1 Validation of Methodology

The behavioural results confirmed the planned research design, where two distinct (low and high) Workload conditions were produced by the variations in the visual memory task and will not be discussed further. In addition to confirming the research design regarding workload, the EEG methodology also required validation. Both the paired tone paradigm (sensory gating) and the oddball paradigm (salience effects) were validated by investigating P200 responses at the somatosensory association cortex. The paired tone validation demonstrated sensory gating as expected, where the second standard tone elicited less deflection at 200 ms as compared to the first standard tone. The oddball tone effect was also observed, such that the deviant second tone displayed greater deflection at the P200 latency as compared to the standard second tone.

5.2 Analysis of Deviance on Sensory Gating

Sensory gating refers to the neural phenomenon of filtering redundant information (Jones et al., 2016). In the present study, both age groups showed sensory gating by attenuating neural responses to redundant stimuli. To signal the need for a handover of tasks in a semi-autonomous vehicle, salient alerts, not subject to sensory gating, are required to obtain driver attention. In the present work, rare second-pair deviant tones replaced the redundant same-frequency second-pair standard tones to investigate whether the deviant tones would overcome the neural tendency to "gate" redundant stimuli. Overall, the second-pair deviant tones showed higher P200 amplitudes when compared to the standard second-pair tones. That said, there were instances where the second-pair deviant tones did not help to overcome neural redundancies, which will be discussed in the following paragraphs. The regions of the brain selected for this research included those along the auditory processing pipeline; primary auditory cortex (the main site of auditory processing), the somatosensory association cortex (where phonological relationships are processed), and the dorsolateral prefrontal cortex (involved in phonological processing and executive function).

It was hypothesized that there would be no effect of Age on increased P200 responses for the deviant second tone in the low-workload condition. The rationale for this hypothesis is that in similar neural evaluations of spatial working memory, older adults seem to be less susceptible to overactivity as a result of low-workload tasks (Causse et al., 2019). This hypothesis was supported at early and later stages of the auditory processing pipeline. However, an unexpected positive effect of Age was found at the somatosensory association cortex, where older age resulted in increased P200 amplitudes in the low-workload condition in response to the second deviant tone. The higher P200 amplitudes for the deviant tone in low-workload conditions was a promising finding for older driver safety, as it suggests that if workload induced by the primary task of driving or by secondary tasks can be controlled, salient stimuli should be sufficient to alert older adults when some driver action is required, such as a handover. To this end, there is hope that with workload-reducing technology in semi-autonomous vehicles, older adults will be supported in driving at older ages than is currently considered standard practice (Holley-Moore & Creighton, 2015). Users will be required to, on occasion, engage in the driving task, however, it is expected that fewer attentional resources will be required as the automation systems improve. The Norman and Bobrow (1975) model of attention supports this expectation, as they suggest that humans and their performance on tasks are limited by their own resources, as well as the data that is available to them. As there are improvements in semi-autonomous vehicles and controls on secondary task involvement as per the findings in this research, auditory alert systems in semi-autonomous vehicles will not only result in safer interactions but will also show promise for the future of driving behaviours in aging populations.

Concerning the second key hypothesis and overcoming sensory gating in high-workload conditions, a general finding was that there was a reduced effect of the deviant second tone for older adults. Evidence for suboptimal sensory gating of salient stimuli in older but not younger adults was most evident at the region of the primary auditory cortex. One explanation for the attenuation of the P200 component in the older group is the Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH), which suggests that older adults allocate more neural resources for lower workload tasks than is expected in a younger adult brain (Reuter-Lorenze & Cappell, 2008). If the CRUNCH hypothesis explains the relative overactivation to auditory stimuli during low-workload conditions of the primary visual tasks, as the task workload increases, it might be expected that the older group had comparatively fewer resources remaining for processing the tones. CRUNCH also explains why older adults showed stronger effects of the deviant tones in the low-workload condition than younger adults, since compensatory mechanisms may be overly attentive to deviant stimuli when the ongoing visual task was easy. However, once there was a sharp increase in the ongoing task demands, there was a concomitant sharp decrease in the older adults' ability to attend to the deviant stimuli (see Figure 16). The findings mentioned above are in line with the literature. For example, Daffner et al. (2011)

collected ERPs to evaluate performance differences on a working memory task vary across the lifespan. Their findings were consistent with the CRUNCH hypothesis, where the older group recruited more neural resources for lower workload tasks than was seen in the younger group. Another study that implemented the auditory oddball paradigm found similar results in line with the CRUNCH hypothesis (van Dinteren et al., 2014). While this study did not manipulate workload, they did find that when comparing neural activity across the lifespan, amplitudes in response to deviant stimuli decreased with older age. The difference in P200 amplitudes observed between age groups is supported by emerging research which suggests that sensory gating is reflexive to individual differences (Vartanian et al., 2013; Zabelina et al., 2015).

The tendency to reach the capacity of neural resources is not limited to older adults. One of the primary constructs behind working memory is that there is a limit on how much the system can handle (Baddeley, 2003). The exact limit has been highly speculated, with Miller (1956) suggesting that the limit lies around seven (give or take two) bits of information, while Cowan proposes that the limit is even smaller, falling somewhere between three and five bits of information (2010). It is generally understood that with age, there is an overall reduction in working memory capacity (Fabiani, 2012). The findings of this study are consistent with the working memory literature, where older adults are reaching their mental capacity at a faster rate than younger adults.

P200 activity at the dorsolateral prefrontal cortex region showed an interaction between Age and Workload, where the older group presented more attenuation than the younger group, but only in the high-workload condition. The finding that overall, the older group presented attenuated neural responses in the high-workload condition is in line with the CRUNCH hypothesis and supports a portion of the hypotheses that were put forth at the beginning of this paper. However, Tone Type played no role in neural activity at the dorsolateral prefrontal cortex, which is the opposite of expectations. Specifically, deviance did not successfully overcome neural redundancies in this region. Previous research suggests that the role of the dorsolateral prefrontal cortex in its relation to auditory processing has less to do with the encoding of auditory stimuli and more to do with controlling responses to stimuli (Plakke & Romanski, 2014). The auditory information presented in this study did not require a response. It is possible that in iterations of this research where a response to auditory information is necessary, activation patterns would be different.

Another plausible explanation for the absence of an effect of Tone Type is due to the role of the dorsolateral prefrontal cortex in visual memory working memory tasks. The dorsolateral prefrontal cortex is believed to be involved in the maintenance and manipulation of visual information (Kim & Cameron, 2016), both of which were very important to the visual memory task that the participants completed in the study. Additionally, the visual memory task required intensive working memory activity, and the dorsolateral prefrontal cortex is said to be the site of the central executive (Chai et al., 2018); a location that is responsible for distributing information to the other model components (Baddeley, 2002; Baddeley & Hitch, 1974). Undoubtedly, this region is highly active due to the visual and working memory task that participants are completing, and it is possible that for this reason, the tones, regardless of their salience, do not affect neural activity.

5.3 Analysis of Tone Type and Stimulus Position on Neural Activation

Results showed a main effect of Tone Type at both the somatosensory association cortex and primary auditory cortex, whereby the first standard tone and second deviant tone resulted in greater neural activity than the second standard tone. While this finding is in line with previous studies implementing the paired click and oddball paradigms (Liebenthal et al., 2003; Lijffijt et al., 2009), within the context of semi-autonomous vehicles, this finding about Tone Type is particularly of interest. In recent years, there has been a shift towards implementing pre-alerts in semi-autonomous vehicles, particularly for handover situations. Van der Heiden et al. (2017) investigated the effect of introducing one or multiple auditory pre-alerts to participants in a simulator and found that this resulted in safer handover situations than those that did not include a pre-alert. While the study supported that pre-alerts would help ensure safe and smooth handover situations, there was no investigation into the effect of repetitive stimuli that over time, become redundant. Therefore, in the future, it may be wise to conduct a similar study across different age groups that evaluate pre-alerts while engaged in task-irrelevant activities, that investigate the impact of incorporating salient auditory tones paired with pre-alerts to maximize auditory processing and provide the safest experience possible.

Chapter 6: Conclusion

Analyses of P200 component amplitudes at the major auditory processing pipeline locations of the brain revealed that, in general, the second-pair deviant tones showed higher P200 amplitudes when compared to the standard second-pair tones. At the start of the auditory processing pipeline, the primary auditory cortex, there was an effect of Age on P200 components in only the high-workload task, where the older group presented more attenuation than the younger group. At the next level of the auditory processing pipeline, and in contrast to expectations, at the somatosensory association cortex, the salient auditory information resulted in a positive effect of older age in the low-workload condition. The final segment of the pipeline discussed in this research includes the dorsolateral prefrontal cortex, where tone salience did not help participants overcome sensory gating, though there was an effect of Age on neural activity in the high-workload condition, where P200 components were attenuated amongst the older group when compared to the younger group.

These findings show that salient auditory information can help to overcome neural redundancies among younger adults, and in some instances, older adults when workload levels are low. This research highlights that auditory processing varies across the lifespan and suggests that the current design, research, and policy in semi-autonomous vehicles, more specifically in auditory alerting systems, should be re-evaluated to consider the needs of different populations. It is critical to evaluate all components of auditory alerting systems to enhance safety features within semi-autonomous vehicles and ensure safe human-computer interactions.

6.1 Limitations

A limitation of this research is that auditory alerts in semi-autonomous vehicles have meanings associated with them and must be acted upon. Participants were exposed to passive auditory information fed throughout the study, and they were not to respond in any way to the tones. Thus, although it was important to investigate aural information that had a high likelihood of being “gated out”, studying active alerts should also be conducted to further address the semi-autonomous vehicle experience.

6.2 Future Work

In future iterations of this work, in line with the final limitation, it would be interesting to inform participants that different auditory information is associated with different meanings or levels of importance to see if the prior knowledge impacts the processing of the auditory stimuli. Additionally, it would be informative to require that users respond to the auditory information, similar to how they might respond in a handover situation in a semi-autonomous vehicle. Furthermore, whereas the present research emphasized visual and auditory information, future research could evaluate whether age and workload effects can be overcome by introducing not only auditory alerts but also vibrotactile alerts.

Finally, Daffner et al. (2011) pointed out the importance of stepping away from the narrative that suggests that changes in cognition across the lifespan are uniform. In future iterations of this research, in addition to evaluating age-related cognitive decline, correlations should be drawn between performance and participant groups (for example, by comparing high-performers to low-performers in addition to age groups). While this research presented differences in older and younger adult neural activity, the intention is not to deem anybody above a certain age as unfit for tasks that involve complex cognitive involvement, such as driving. Rather, the hope is that by unravelling the intricacies behind auditory processing on a neurological level, this knowledge can be leveraged to improve safety for older drivers.

Chapter 7: Appendices

Appendix A – Ethics Clearance

Office of Research Ethics
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Ottawa, Ontario K1S 5B6
613-520-2600 Ext: 4085
ethics@carleton.ca

CERTIFICATION OF INSTITUTIONAL ETHICS CLEARANCE

The Carleton University Research Ethics Board-B (CUREB-B) has granted ethics clearance for the changes to protocol to research project described below and research may now proceed. CUREB-B is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS2).

Ethics Clearance ID: Project # 104917 13-094

Principal Investigator: Dr. Chris Herdman

Co-Investigator(s) (If applicable): **Dr. Chris Herdman (Primary Investigator)**
Dr. Kathleen Van Benthem (Other)
Stefanie Gard (Student Researcher)
Melanie Turbanian (Student Researcher)
Caitlin Thibodeau (Student Researcher)
Heather Wright (Collaborator)
Jocelyn Keillor (Collaborator)

Project Title: **An Evaluation of Workload in Visual Processing and Storage Tasks Using an Auditory Oddball Paradigm: An ERP Study**

Funding Source:

Effective: **September 19, 2019** Expires: **September 30, 2020**.

Upon reasonable request, it is the policy of CUREB, for cleared protocols, to release the name of the PI, the title of the project, and the date of clearance and any renewal(s).

During the course of the study, if you encounter an adverse event, material incidental finding, protocol deviation or other unanticipated problem, you must complete and submit a Report of Adverse Events and Unanticipated Problems Form, found here: https://carleton.ca/researchethics/forms-and-templates/

Please email the Research Compliance Coordinators at ethics@carleton.ca if you have any questions.

CLEARED BY: **Date: September 19, 2019**

[redacted]

Natasha Artemeva, PhD, Chair, CUREB-B

[redacted]

Janet Mantler, PhD, Vice Chair, CUREB-B

Appendix B – Recruitment Poster

Carleton UNIVERSITY

Participate in an EEG study investigating cognitive workload

To participate in this study, you must be:

✓ **50 years of age or older**

✓ Normal hearing

✓ Right handed

✓ Comfortable in the English language

This is a 120-minute study. You will be asked to wear an electroencephalography (EEG) headcap while playing a grid matching game on a computer.

Participants will be compensated with a parking pass and Refreshments (approx. value $20.00)

The ethics protocol for this project has been reviewed and cleared by the Carleton University Research Ethics Board. If you have any ethical concerns with the study, please contact ethics@carleton.ca.

Preparation: Participants are asked to come prepared to wash their hair in a basin upon arrival to the lab. Shampoo, clean towels and a private room will be provided. Participants are advised that the EEG net will be frequently moistened throughout the recording session. Therefore, hair may remain damp throughout the experimental session.

Please contact the researcher Melanie Turabian at melanieturabian@cmail.carleton.ca for more information or to sign up.

Appendix C – Informed Consent

INFORMED CONSENT FORM

The purpose of an informed consent is to ensure that you understand the purpose of the study and the nature of your involvement. The informed consent has to provide sufficient information such that you have the opportunity to determine whether you wish to participate in the study. This study has received clearance by the Carleton University Psychology Research Ethics Board (Ethics Approval Protocol #: 104917 13-094). Please ask the researcher to clarify any concerns that you may have after reading this form.

STUDY TITLE

An Evaluation of Workload in Visual Processing and Storage Tasks Using an Auditory Oddball Paradigm: An ERP Study

PURPOSE

In this study, we are interested in the electrophysiological correlates of different types of visual memory tasks. We are interested in determining whether patterns of electrophysiological activity change with task demands and age.

TASK

For this study you will be performing a variety of computerized visual tasks while wearing an EEG net. While performing these tasks, you will also hear a series of tones in the background. These tones are task-irrelevant, and can be ignored. We will explain these visual tasks in further detail, and you will get a chance to practice each task and ask questions before the experiment.

DURATION, LOCALE & COMPENSATION

Testing will take place in VSIM 1214 and will take approximately 2 hours to complete. Your will receive 2.0 credits for your participation or a free parking pass and substantial refreshments, value $20.00 (if adult from the community).

EEG TESTING: COMMON QUESTIONS AND CONCERNS

What is an EEG and what is the ERP technique?

An electroencephalogram (EEG) is a non-intrusive procedure where a net is worn on the head and used to measure the electrical activity at your scalp. In this experiment, we are averaging the EEG pattern related to a specific event.

What will my EEG data be used for?

We are looking at aggregate EEG data in order to learn more about the typical patterns of brain activity associated with different cognitive tasks. This information cannot be used to diagnose any sort of neurological impairment an individual may have.

If you have any additional questions or concerns, please ask the researcher today, or contact any of the principal investigators at a later date.

POTENTIAL RISKS/DISCOMFORT

The EEG system in this study presents no physical risk to participants. All equipment is operated within standard safety procedures. The EEG net is non-abrasive with 128 soft sponges that create a harmless micro-interface between the EEG system and the scalp. The computerized tasks used in this study are commonly used visual memory tasks that do not evoke anxiety.

ANONYMITY/CONFIDENTIALITY

All information will be kept anonymous. Results will only be described in aggregate data and identification of individual results will not be possible.

RIGHT TO WITHDRAW/OMIT

Participation in this study is entirely voluntary. At any point during the experiment you have the right to withdraw without penalty.

RESEARCH PERSONNEL

The following individuals are involved in this research project and may be contacted at any time if you have further questions about this project, its purpose or concerns about how it was conducted:

NAME	TITLE	DEPARTMENT	EMAIL	PHONE
Chris Herdman	PhD	Institute of Cognitive Science	Chris.herdman@carleton.ca	520-2600 x 2487
Kathleen Van Benthem	PhD	Institute of Cognitive Science	kathy_vanbenthem@carleton.ca	520-2600 x 2487
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Caitlin Thibodeau	100996996	Cognitive Science (FASS)	CaitlinThibodeau@cmail.carleton.ca	520-2600 x 2487

Other Contacts: Should you have any ethical concerns with the study, please contact the REB Chair, Carleton University Research Ethics Board-B (by phone: 613-520-2600 ext. 4085 or by email: ethics@carleton.ca). For all other questions about the study, please contact the researcher

Signatures

I have read the above form and understand the conditions of my participation. My participation in this study is voluntary, and I understand that if at any time I wish to leave the experiment, I may do so without having to give an explanation and with no penalty whatsoever. Furthermore, I am also aware that the data gathered in this study are confidential and anonymous with respect to my personal identity. My signature indicates that I agree to participate in this study.

Date______________________

Participant's Full Name: ___________________________________

Participant's Signature: ____________________________________

Researcher's Name: ____________________________________

Researcher's Signature: ___________________________________

Appendix D – Demographics Questionnaire

Age: ____

Gender:	Male	Female	Prefer not to answer

Please circle your responses to the following questions:

Have you previously had a concussion?	Yes	No	
Do you have normal to corrected vision?	Yes	No	
Do you have any hearing impairments?	Yes	No	
Are right or left-handed?	Right	Left	Both
Is English your first language?	Yes	No	

1. How alert do you feel right now? (1 – Not at all alert, 10 – Very alert)

1 2 3 4 5 6 7 8 9 10

Not at all Neutral Very alert

2. Approximately how many hours of sleep did you get last night?

0-4 5-6 7-8 9 or more hours

3. I last ate…

Within 30 minutes Within the last hour Within 2 hours Over 2 hours ago

Appendix E – Debriefing Form

DEBRIEFING

Thank you for your participation in this study! The purpose of this study was to investigate patterns of electrical activity in the brain under varying levels of task difficulty. We are interested in determining if the ERP techniques used in the lab today can help us identify a specific electrophysiological signature of the brain activity during a high cognitive workload situation. Furthermore, we are interested in determining whether this electrophysiological signature is the same for high workload situations in different types of cognitive tasks. The findings from this study will contribute to a growing body of work that investigates electrophysiological responses to cognitive workload in younger and older adults, and will help researchers develop new techniques to compare performance on different types of tasks including real world high workload situations such as operating an aircraft. If you are interested in learning more about visuospatial working memory, then please see the following:

Luck, S. J. (2005). *An introduction to the event-related potential technique*. The MIT Press.

Miller, M.W. et al. (2010). A novel approach to the physiological measurement of workload. *International Journal of Psychophysiology,* 80, 75-78

This study has received clearance by the Carleton University Psychology Research Ethics Board (Ethics Approval: Protocol #: 104917 13-094).

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Other Contacts: Should you have any ethical concerns with the study, please contact the REB Chair, Carleton University Research Ethics Board-B (by phone: 613-520-2600 ext. 4085 or by email: ethics@carleton.ca). For all other questions about the study, please contact the researcher

References

Ahnaou, A., Biermans, R., & Drinkenburg, W. H. (2016). Modulation of mGlu2 Receptors, but Not PDE10A Inhibition Normalizes Pharmacologically-Induced Deviance in Auditory Evoked Potentials and Oscillations in Conscious Rats. *PLOS ONE*, *11*(1). https://doi.org/10.1371/journal.pone.0147365

Andrade, J. (2001). An introduction to working memory. *Working Memory in Perspective*, 3–30. https://doi.org/10.4324/9780203194157_chapter_1

Au, K. F. (2011). Advances in knitting technology. *Elsevier*. https://doi.org/10.1533/9780857090621

Baddeley, A. (2002). Fractionating the Central Executive. *Principles of Frontal Lobe Function*, 246–260. https://doi.org/10.1093/acprof:oso/9780195134971.003.0016

Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. https://doi.org/10.1038/nrn1201

Baddeley, A. D., & Hitch, G. (1974). Working Memory. *Psychology of Learning and Motivation*, 47–89. https://doi.org/10.1016/s0079-7421(08)60452-1

Banks, V. A., Eriksson, A., O'Donoghue, J., & Stanton, N. A. (2018). Is partially automated driving a bad idea? Observations from an on-road study. *Applied Ergonomics*, *68*, 138–145. https://doi.org/10.1016/j.apergo.2017.11.010

Bourisly, A. K., & Shuaib, A. (2018). Neurophysiological effects of aging: A P200 ERP study. *Translational Neuroscience*, *9*(1), 61–66. https://doi.org/10.1515/tnsci-2018-0011

Boutros, N. N., Korzyukov, O., Jansen, B., Feingold, A., & Bell, M. (2004). Sensory gating deficits during the mid-latency phase of information processing in medicated schizophrenia patients. *Psychiatry Research*, *126*(3), 203–215. https://doi.org/10.1016/j.psychres.2004.01.007

Bustamante, E. A., Bliss, J. P., & Anderson, B. L. (2007). Effects of varying the threshold of alarm systems and workload on human performance. *Ergonomics*, *50*(7), 1127–1147. https://doi.org/10.1080/00140130701237345

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*(1), 85–100. https://doi.org/10.1037/0882-7974.17.1.85

Carlstedt, R. A., & Balconi, M. (2019). *Handbook of sport neuroscience and psychophysiology*. Routledge.

Carsten, O., Lai, F. C., Barnard, Y., Jamson, A. H., & Merat, N. (2012). Control Task Substitution in Semiautomated Driving. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *54*(5), 747–761. https://doi.org/10.1177/0018720812460246

Causse, M., Chua, Z. K., & Rémy, F. (2019). Influences of age, mental workload, and flight experience on cognitive performance and prefrontal activity in private pilots: a fNIRS study. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-44082-w

Chai, W. J., Abd Hamid, A. I., & Abdullah, J. M. (2018). Working Memory From the Psychological and Neurosciences Perspectives: A Review. *Frontiers in Psychology*, *9*. https://doi.org/10.3389/fpsyg.2018.00401

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. L. Erlbaum Associates.

Society for Neuroscience. (2021). *Interactive Brain Model*. BrainFacts.org. https://www.brainfacts.org/3d-brain#intro=true.

Cowan, N. (2010). The Magical Mystery Four. *Current Directions in Psychological Science*, *19*(1), 51–57. https://doi.org/10.1177/0963721409359277

Daffner, K. R., Chong, H., Sun, X., Tarbi, E. C., Riis, J. L., McGinnis, S. M., & Holcomb, P. J. (2011). Mechanisms Underlying Age- and Performance-related Differences in Working Memory. *Journal of Cognitive Neuroscience*, *23*(6), 1298–1314. https://doi.org/10.1162/jocn.2010.21540

Davis, S. W., Dennis, N. A., Daselaar, S. M., Fleck, M. S., & Cabeza, R. (2007). Que PASA? The Posterior-Anterior Shift in Aging. *Cerebral Cortex*, *18*(5), 1201–1209. https://doi.org/10.1093/cercor/bhm155

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. Journal of neuroscience methods, 134(1), 9-21.

Disengagement Reports. California DMV. (2019). https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/disengagement-reports/.

Fabiani, M. (2012). It was the best of times, it was the worst of times: A psychophysiologist's view of cognitive aging. *Psychophysiology*, *49*(3), 283–304. https://doi.org/10.1111/j.1469-8986.2011.01331.x

Freedman, R., Adler, L. E., Gerhardt, G. A., Waldo, M., Baker, N., Rose, G. M., Drebing, C., Nagamoto, H., Bickford-Wimer, P., Franks, R. (1987). Neurobiological Studies of Sensory Gating in Schizophrenia. *Schizophrenia Bulletin*, *13*(4), 669–678. https://doi.org/10.1093/schbul/13.4.669

Frith, C. D. (1979). Consciousness, Information Processing and Schizophrenia. *British Journal of Psychiatry*, *134*(3), 225–235. https://doi.org/10.1192/bjp.134.3.225

Gmehlin, D., Kreisel, S. H., Bachmann, S., Weisbrod, M., & Thomas, C. (2011). Age Effects on Preattentive and Early Attentive Auditory Processing of Redundant Stimuli: Is Sensory Gating Affected by Physiological Aging? *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *66A*(10), 1043–1053. https://doi.org/10.1093/gerona/glr067

Harrison, M. (2004). Interior noise: assessment and control. *Vehicle Refinement*, 145–233. https://doi.org/10.1016/b978-075066129-4/50006-7

Hoffmann, U., Vesin, J.-M., Ebrahimi, T., & Diserens, K. (2008). An efficient P300-based brain–computer interface for disabled subjects. *Journal of Neuroscience Methods*, *167*(1), 115–125. https://doi.org/10.1016/j.jneumeth.2007.03.005

Holley-Moore, G., & Creighton, H. (2015, June). *The Future of Transport in an Ageing Society*. https://www.ageuk.org.uk/globalassets/age-uk/documents/reports-and-publications/reports-and-briefings/active-communities/rb_june15_the_future_of_transport_in_an_ageing_society.pdf.

J3016B: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles - SAE International. (2018). https://www.sae.org/standards/content/j3016_201806.

Jamson, A. H., Merat, N., Carsten, O. M. J., & Lai, F. C. H. (2013). Behavioural changes in drivers experiencing highly-automated vehicle control in varying traffic conditions. *Transportation Research Part C: Emerging Technologies*, *30*, 116–125. https://doi.org/10.1016/j.trc.2013.02.008

Jin, L., Guo, B., Jiang, Y., Wang, F., Xie, X., & Gao, M. (2018). Study on the Impact Degrees of Several Driving Behaviors When Driving While Performing Secondary Tasks. *IEEE Access*, *6*, 65772–65782. https://doi.org/10.1109/access.2018.2878150

Jones, L. A., Hills, P. J., Dick, K. M., Jones, S. P., & Bright, P. (2016). Cognitive mechanisms associated with auditory sensory gating. *Brain and Cognition*, *102*, 33–45. https://doi.org/10.1016/j.bandc.2015.12.005

Kim, H., & Cameron, C. E. (2016). Implications of Visuospatial Skills and Executive Functions for Learning Mathematics. *AERA Open*, *2*(4), 233285841667512. https://doi.org/10.1177/2332858416675124

Knoefel, F., Wallace, B., Goubran, R., Sabra, I., & Marshall, S. (2019). Semi-Autonomous Vehicles as a Cognitive Assistive Device for Older Adults. *Geriatrics*, *4*(4), 63. https://doi.org/10.3390/geriatrics4040063

Liebenthal, E., Ellingson, M. L., Spanaki, M. V., Prieto, T. E., Ropella, K. M., & Binder, J. R. (2003). Simultaneous ERP and fMRI of the auditory cortex in a passive oddball paradigm. *NeuroImage*, *19*(4), 1395–1404. https://doi.org/10.1016/s1053-8119(03)00228-3

Lijffijt, M., Lane, S. D., Meier, S. L., Boutros, N. N., Burroughs, S., Steinberg, J. L., Moeller, F., Swann, A. C. (2009). P50, N100, and P200 sensory gating: Relationships with behavioral inhibition, attention, and working memory. *Psychophysiology*, *46*(5), 1059–1068. https://doi.org/10.1111/j.1469-8986.2009.00845.x

Lin, C.-T., Huang, T.-Y., Liang, W.-C., Chiu, T.-T., Chao, C.-F., Hsu, S.-H., & Ko, L.-W. (2009). Assessing Effectiveness of Various Auditory Warning Signals in Maintaining Drivers' Attention in Virtual Reality-Based Driving Environments. *Perceptual and Motor Skills*, *108*(3), 825–835. https://doi.org/10.2466/pms.108.3.825-835

Litman, T. (2021). *Autonomous Vehicle Implementation Predictions*. https://vtpi.org/avip.pdf.

Lv, C., Cao, D., Zhao, Y., Auger, D. J., Sullman, M., Wang, H., Dutka, L. M., Skrypchuk, L., Mouzakitis, A. (2018). Analysis of autopilot disengagements occurring during autonomous vehicle testing. *IEEE/CAA Journal of Automatica Sinica*, *5*(1), 58–68. https://doi.org/10.1109/jas.2017.7510745

Magstim EGI. (n.d.). The Geodesic Sensor Net. https://www.egi.com/images/stories/manuals/Printed%20IFUs%20with%20New%20Notified%20Body/HC_GSN_channel_map_128_8403486-54_20181207.pdf.

Maltz, M., Sun, H., Wu, Q., & Mourant, R. (2004). In-Vehicle Alerting System for Older and Younger Drivers: Does Experience Count? *Transportation Research Record: Journal of the Transportation Research Board*, *1899*(1), 64–70. https://doi.org/10.3141/1899-08

Marshall, D., Chrysler, S., & Smith, K. (2014, May 31). *Older Drivers' Acceptance of In-Vehicle Systems and the Effect it has on Safety*. TRID. https://trid.trb.org/view/1331080.

McCall, R., McGee, F., Mirnig, A., Meschtscherjakov, A., Louveton, N., Engel, T., & Tscheligi, M. (2018, June 11). *A taxonomy of autonomous vehicle handover situations*. Transportation Research Part A: Policy and Practice. https://www.sciencedirect.com/science/article/pii/S0965856417311072.

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97. https://doi.org/10.1037/h0043158

Morando, A., Gershon, P., Mehler, B., & Reimer, B. (2020). Driver-initiated Tesla Autopilot Disengagements in Naturalistic Driving. *12th International Conference on Automotive*

User Interfaces and Interactive Vehicular Applications. https://doi.org/10.1145/3409120.3410644

Møller, A. R. (2012). In *Hearing: anatomy, physiology, and disorders of the auditory system*. essay, Plural.

Nagaraj, N., Kennett, S., Levisee, M., & Atcherson, S. (2015). Overview of Central Auditory Processing Deficits in Older Adults. *Seminars in Hearing*, *36*(03), 150–161. https://doi.org/10.1055/s-0035-1555118

Nees, M. A., Helbein, B., & Porter, A. (2016). Speech Auditory Alerts Promote Memory for Alerted Events in a Video-Simulated Self-Driving Car Ride. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *58*(3), 416–426. https://doi.org/10.1177/0018720816629279

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology*, *7*(1), 44–64. https://doi.org/10.1016/0010-0285(75)90004-3

Osmanski, M. S., & Wang, X. (2015). Behavioral Dependence of Auditory Cortical Responses. *Brain Topography*, *28*(3), 365–378. https://doi.org/10.1007/s10548-015-0428-4

Plakke, B., & Romanski, L. M. (2014). Auditory connections and functions of prefrontal cortex. *Frontiers in Neuroscience*, *8*. https://doi.org/10.3389/fnins.2014.00199

Pujol, R. (2020). *Journey into the world of hearing*. Cochlea. http://www.cochlea.eu/en/auditory-brain.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive Aging and the Compensation Hypothesis. *Current Directions in Psychological Science*, *17*(3), 177–182. https://doi.org/10.1111/j.1467-8721.2008.00570.x

Schnupp, J., Nelken, E., & King, A. (n.d.). *dB HL - Sensitivity to Sound - Clinical Audiograms*. dB HL - Sensitivity to Sound - Clinical Audiograms | Auditory Neuroscience. http://auditoryneuroscience.com/acoustics/clinical-audiograms.

Shen, C.-L., Chou, T.-L., Lai, W.-S., Hsieh, M. H., Liu, C.-C., Liu, C.-M., & Hwu, H.-G. (2020). P50, N100, and P200 Auditory Sensory Gating Deficits in Schizophrenia Patients. *Frontiers in Psychiatry*, *11*. https://doi.org/10.3389/fpsyt.2020.00868

Trans Cranial Technologies ltd. (2012). *Cortical Functions*. TCT Research. http://www.trans-cranial.com/manuals/.

Turabian, M., Van Benthem, K., & Herdman, C. M. (2020). Impairments in Early Auditory Detection Coincide with Substandard Visual-Spatial Task Performance in Older Age: An ERP Study. *Communications in Computer and Information Science*, 110–118. https://doi.org/10.1007/978-3-030-60703-6_14

van der Heiden, R. M. A., Iqbal, S. T., & Janssen, C. P. (2017). Priming Drivers before Handover in Semi-Autonomous Cars. *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3025453.3025507

van Dinteren, R., Arns, M., Jongsma, M. L., & Kessels, R. P. (2014). Combined frontal and parietal P300 amplitudes indicate compensated cognitive processing across the lifespan. *Frontiers in Aging Neuroscience*, *6*. https://doi.org/10.3389/fnagi.2014.00294

Vartanian, O., Jobidon, M.-E., Bouak, F., Nakashima, A., Smith, I., Lam, Q., & Cheung, B. (2013). Working memory training is associated with lower prefrontal cortex activation in a divergent thinking task. *Neuroscience*, *236*, 186–194. https://doi.org/10.1016/j.neuroscience.2012.12.060

Wiese, E. E., & Lee, J. D. (2004). Auditory alerts for in-vehicle information systems: The effects of temporal conflict and sound parameters on driver attitudes and performance. *Ergonomics*, *47*(9), 965–986. https://doi.org/10.1080/00140130410001686294

Wogalter, M. S., Conzola, V. C., & Smith-Jackson, T. L. (2002). Research-based guidelines for warning design and evaluation. *Applied Ergonomics*, *33*(3), 219–230. https://doi.org/10.1016/s0003-6870(02)00009-1

World Health Organization. (2018, July 26). *Deafness Prevention Estimates*. World Health Organization. https://www.who.int/deafness/estimates/en/.

Zabelina, D. L., O'Leary, D., Pornpattananangkul, N., Nusslock, R., & Beeman, M. (2015). Creativity and sensory gating indexed by the P50: Selective versus leaky sensory gating in divergent thinkers and creative achievers. *Neuropsychologia*, *69*, 77–84. https://doi.org/10.1016/j.neuropsychologia.2015.01.034