Age-Related Differences in Multimodal Information Processing and their Implications for Adaptive Display Design

by

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"For I know the plans I have for you"

Jeremiah 29:11

DEDICATION

To my father, mother, and late uncle Reverend James H. Pitts, Sr.

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ABSTRACT

In many data-rich, safety-critical environments, such as driving and aviation, multimodal displays (i.e., displays that present information in visual, auditory, and tactile form) are employed to support operators in dividing their attention across numerous tasks and sources of information. However, limitations of this approach are not well understood. Specifically, most research on the effectiveness of multimodal interfaces has examined the processing of only two concurrent signals in different modalities, primarily in vision and hearing. Also, nearly all studies to date have involved young participants only.

The goals of this dissertation were therefore to (1) determine the extent to which people can notice and process three unrelated concurrent signals in vision, hearing and touch, (2) examine how well aging modulates this ability, and (3) develop countermeasures to overcome observed performance limitations. Adults aged 65+ years were of particular interest because they represent the fastest growing segment of the U.S. population, are known to suffer from various declines in sensory abilities, and experience difficulties with divided attention.

Response times and incorrect response rates to singles, pairs, and triplets of visual, auditory, and tactile stimuli were significantly higher for older adults, compared to younger participants. In particular, elderly participants often failed to notice the tactile signal when all three cues were combined. They also frequently falsely reported the presence of a visual cue

when presented with a combination of auditory and tactile cues. These performance breakdowns were observed both in the absence and presence of a concurrent visual/manual (driving) task. Also, performance on the driving task suffered the most for older adult participants and with the combined visual-auditory-tactile stimulation. Introducing a half-second delay between two stimuli significantly increased response accuracy for older adults.

This work adds to the knowledge base in multimodal information processing, the perceptual and attentional abilities and limitations of the elderly, and adaptive display design. From an applied perspective, these results can inform the design of multimodal displays and enable aging drivers to cope with increasingly data-rich in-vehicle technologies. The findings are expected to generalize and thus contribute to improved overall public safety in a wide range of complex environments.

CHAPTER 1

Introduction

Many highly demanding, safety-critical environments, such as driving, aviation, and medicine, require operators to divide their attentional resources among increasing numbers of tasks and sources of information. For example, the driver of an automobile may receive driving directions from a Global Positioning System (GPS), shown on a visual navigation display. While reviewing this information, the driver is alerted by an auditory signal warning that a leading vehicle has suddenly applied brakes, and a vibration to the steering wheel indicates that the vehicle is drifting out of the lane. In this particular situation, the driver receives, simultaneously, information about three different events in three different modalities (vision, hearing and touch), and needs to notice, interpret and respond quickly and appropriately to each of them.

Multimodal displays, i.e., displays that present information via multiple sensory channels, have been introduced as a promising means of reducing visual data overload and improving multitasking and attention management (e.g., Giang, Santhakumaran, Masnavi, Glussich, Kline, Chui, Burns, Histon, & Zelek, 2010; Spence & Driver, 1997a; Wickens, 2008). However, the limitations of multimodal information processing and display design are not fully understood. One major gap in the literature is the very limited number of studies on the ability to timeshare more than two simultaneous signals in separate sensory channels. Of the few studies that have examined this question, nearly all employed redundant cues, i.e., cues that provided the same information or referred to the same event (e.g., Hecht, Reiner, & Halevy, 2006; Murata, Kanbayashi, & Hayami, 2013; Lees et al., 2012). In case of redundant cues, it is sufficient if at least one of them is being noticed. However, in the above example, the driver would need to detect and process all three signals as they relate to different tasks and events. Anecdotal evidence, and the only empirical study (Hecht & Reiner, 2009) addressing this situation, suggest that a person will likely fail to notice one or more signals when presented with three or more non-redundant multimodal cues at the same time.

Another important yet unanswered question regarding the use of multimodal displays relates to the effect of biological aging on the ability to divide attention between multiple sensory modalities. Generally, breakdowns in attention allocation and information processing are more likely to occur in the elderly. They often suffer from declines in sensory abilities (e.g., Li & Lindenberger, 2002; Stuart-Hamilton, 2012) and also experience difficulties with divided attention (e.g., McDowd, Vercruyssen, & Birren, 1991; Somberg & Salthouse, 1982). Still, the vast majority of studies on multimodal displays has involved younger participants only. As a result, it is not clear whether older adults can cope with and benefit from multimodal displays. This is an important question because adults aged 65 years and older represent the fastest growing age group in the United States. Within the next 14 years, they are expected to live longer, work longer, and drive longer. In particular, by the year 2030, they will make up 21% of the total U.S. population and more than 25% of the U.S. workforce (He, Sengupta, Velkoff, & DeBarros, 2005; Stutts, Martell, & Staplin, 2009; U.S. Census Bureau, 2008). Individuals in this age group are expected to contribute to 25% of all fatal automotive accidents, over the same time period. To reduce the risk of accidents, the automotive industry has introduced assistive technologies to modern car cockpits, such as blind spot notification, lane departure, and collision warning. These technologies are associated with new notifications and alerts, some of them in previously underutilized sensory channels, and thus increase the probability of a person being faced with two or more unrelated sources of information, especially during highly-critical, off-nominal situations. To ensure the usefulness of assistive technologies for all drivers, it will be important to consider perceptual and attentional limitations in older adults.

Before studies are conducted to examine the effectiveness and limitations of multimodal displays, a more valid and reliable ‘crossmodal matching’ procedure needs to be developed. Crossmodal matching refers to equating the perceived salience of multimodal stimuli to one-another (Colman, 2008). Currently, more than an estimated 95% of studies on multimodal displays fail to perform this step prior to the actual experiment, and therefore risk confounding modality with other signal properties, such as salience. The remaining 5% of studies employ some form of crossmodal matching, but provide very little information about the specific procedure and/or differ considerably in their approach.

The body of work presented in this dissertation addresses the above gaps in the multimodal information processing literature. The specific aims are to:

1. Develop a reliable and efficient crossmodal matching technique
2. Establish and compare the extent to which younger and older adults can detect and process non-redundant cues that appear concurrently in vision, hearing, and touch
    i. Examine this ability both in isolation and while performing a concurrent task
3. Develop and test a countermeasure to overcome limitations that may be identified in #2 and #3

The following sections will provide an overview of multimodal information presentation and processing and highlight gaps in the literature. Next, aging-related deficits in attention and information processing that are relevant to multimodal display design will be described in detail, in addition to potential countermeasures to overcome these challenges. Finally, crossmodal matching will be discussed in more depth.

Multimodal Information Presentation in Support of Attention Management

Traditionally, human-machine interfaces have relied heavily on the visual channel, in part because of the fairly high rate of information transfer that this modality affords. However, in a number of work environments, this tendency, in combination with the introduction of more complex technologies and associated tasks/displays, has resulted in visual data overload and associated performance breakdowns. These problems motivated the increased use of auditory information to offload the visual modality.

Attributes of auditory signals include their frequency (perceived as pitch), volume (loudness), and tempo and rhythm (combination of speed, rate, and rhythm; Giang et al., 2010; Walker & Kramer, 2004). Auditory signals are highly effective for alerting and directing attention because they are salient (Wickens & McCarley, 2007), omnidirectional (not requiring a specific body orientation), and can be manipulated to create recognizable patterns (Brewster, 1994; Deutsch, 1986). However, in some environments, the auditory channel is now being used extensively, leading to complaints about auditory clutter (by airline pilots, for example). To overcome both visual and auditory overload, more recent interface designs have introduced tactile cues (e.g., Calvert, Spence, & Stein, 2004; Sarter, 2006; Scott & Gray, 2008; Wickens, 2008), either as an alternative or supplementary means of information transfer (e.g., Ho, Tan, & Spence, 2005; Mohebbi, Gray, & Tan, 2009; Sklar & Sarter, 1999; Spence & Driver, 1997).

The sense of touch offers a number of benefits as a communication channel in human-machine interfaces (Jones & Sarter, 2008). For example, tactile signals are (1) high in temporal and spatial sensitivity, (2) capable of capturing one's attention in a less intrusive fashion than auditory signals, (3) omnidirectional, (4) proximal – in direct contact with the body – and thus well suited for creating private displays that avoid interrupting others, and (5) stimulation can be applied to a large number of areas on the body. While touch provides the above benefits, it is also important to acknowledge that compared to vision and audition, the amount and complexity of information that can be presented via this channel is relatively small.

The distribution of information across the visual, auditory, and tactile channels is referred to as multimodal information presentation. Multimodal displays were introduced to support operator performance in data-rich environments. Their development was based on Multiple Resource Theory (MRT). MRT posits that humans have limited and varied pools of attentional resources (Wickens, 1980, 1984, 2002, 2008; Wickens & Liu, 1988) that are associated with three main dimensions: processing stage (perception/cognition/response), processing code (verbal and spatial), and modality (visual – both focal and ambient – , auditory, and tactile), as seen in Figure 1.1.

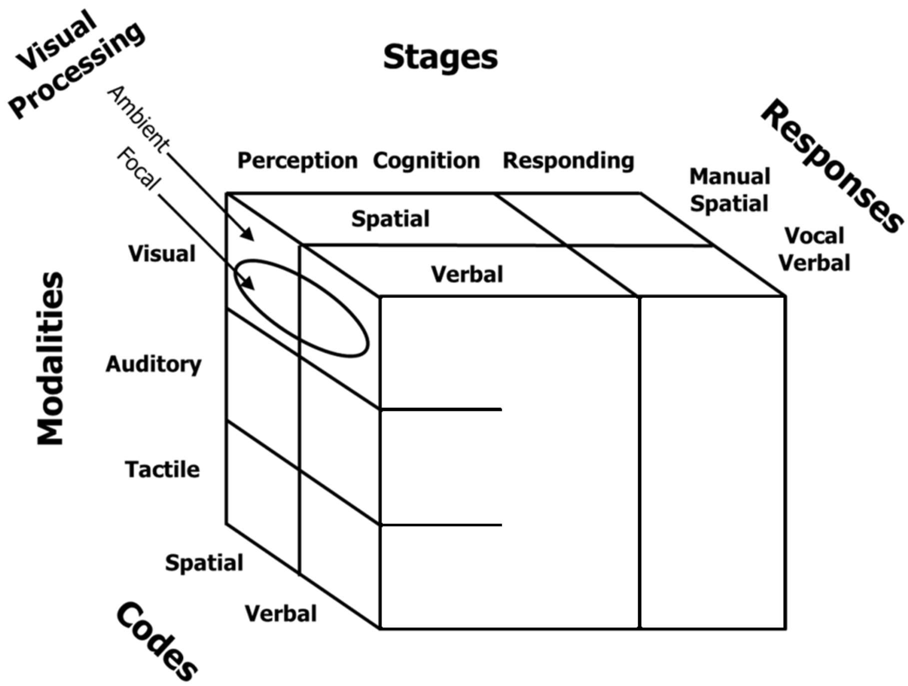

Figure 1.1 The proposed structure of processing resources (adopted from MRT: Wickens, 2008) Attentional resources associated with respective dimensions

MRT assumes partial independence of these attentional resources, and therefore predicts that more tasks and information can be processed simultaneously if they are distributed across multiple sensory channels, thus avoiding resource competition. This prediction has been supported by numerous studies on multimodal information processing and presentation in a variety of application domains, including aviation (e.g., Smith, Clegg, Heggestad, & Hopp-Levine, 2009; Tannen, 2001), driving (e.g., Liu, 2001; Mohebbi, Gray, & Tan, 2009), military (e.g., Oskarsson, Eriksson, & Carlander, 2012), medicine (e.g., Ferris & Sarter, 2011), and space (e.g., Chen, Haas, & Barnes, 2007). Demonstrated benefits of distributing information across modalities include not only reduced visual data overload, but also improved timesharing, more effective attention and interruption management, and an overall increase in bandwidth (e.g., Brickman, Hettinger, & Haas, 2000; Ho, Nikolic, & Sarter, 2001; Latorella, 1999).

The Processing of Two Concurrent Multimodal Signals

The vast majority of studies to date have tested the feasibility and effectiveness of employing only two modalities at a time, such as visual-auditory, visual-tactile, or auditory-tactile combinations (e.g., Bronkhorst, Veltman, Van Breda, 1996; Fitch, Kiefer, Hankey, & Kleiner, 2007; Spence & Driver, 1997). Integrating findings from these studies, recent meta-analyses concluded that adding a second modality improves performance by reducing response times and improving accuracy. Specifically, Burke, Prewett, Gray, Yang, Stilson, Coovert, Elliot, & Redden (2006) showed these gains for combined visual-auditory and visual-tactile feedback while, more recently, Lu, Wickens, Prinet, Hutchins, Sarter, & Sebok (2013) demonstrated performance benefits for auditory-tactile, auditory-visual, and redundant auditory-visual cues to support interruption management.

While the above analyses summarized findings from studies where two different tasks were presented in different modalities, much research in this area has focused on redundant cues, i.e., cues that provide the same information or refer to the same event using different modalities. A prototypical example of redundant messaging is an in-vehicle low fuel notification that presents a signal in both visual and auditory form to increase the likelihood that the event will be noticed. Miller (1982) was one of the first to explore the use of redundancy. In his experiment, participants were instructed to respond to a simple light, tone, or a combination of both – referred to as a ‘bimodal’ cue. He measured response times to each event and found that participants responded faster to the bimodal combination (326 milliseconds (msec)) compared to the light (412 msec) or tone (409 msec) in isolation. These multisensory gains have also been demonstrated in a number of applied contexts, most notably driving. For example, drivers have been found to respond significantly faster to navigation messages that were presented in bimodal visual-tactile form, compared to either modality alone (Van Erp & Van Veen, 2004). The same performance benefits were observed for combined auditory-tactile collision avoidance alerts, compared to unimodal auditory or tactile cues (Ho, Reed & Spence, 2007).

The Processing of Three Multimodal Signals

Very few studies have examined concurrent information presentation in more than two modalities (e.g., Diederich & Colonius, 2004; Hecht, Reiner, & Halevy, 2006; Lees et al., 2012; Oskarsson, Eriksson, & Carlander, 2012). Nearly all of these studies employed redundant cues. For example, Hecht, Reiner, & Halevy (2006) presented participants with redundant pairs and triplets of visual, auditory, and tactile (referred to as trimodal) cues, and found that they responded fastest when all three cues were presented at the same time. The detection task in their study was performed in the absence of a second on-going task. However, Politis, Brewster & Pollick (2014) reported the same finding in the context of a driving task. They presented drivers with warning signals about braking events from a lead vehicle, which appeared as singles, doubles, and triplets of visual, auditory, and tactile stimuli. Overall, in experiments that use redundant cues, response times to trimodal (simultaneous presentation of visual, auditory, and tactile cues) and bimodal cues were the shortest, compared to unimodal (single stimulus) signals, but not necessarily different from each other (e.g., Hecht, Reiner, & Halevy, 2006; Oskarsson, Eriksson, & Carlander, 2012: Rovelo et al. 2012; Vitense, Jacko, & Emery, 2003).

The only study, to date, that employed non-redundant pairs and triplets of simultaneous multimodal cues (Hecht & Reiner, 2009) found that participants failed to detect some of these signals. In particular, this study presented participants with 7 types of visual (V), auditory (A), and haptic (H; force) cues/cue combinations (that is, V, A, H, VA, VH, AH, and VAH).

Their study employed the sensory dominance paradigm (Colavita, 1974), meaning that, in each trial, 80% of cues were unimodal and 20% were bi- or trimodal. Each participant was presented with a total of 4,000 cue/cue combinations, and the duration of each event was 600 msec. When cues were presented in pairs, most errors involved noticing only the visual cues while missing the auditory and haptic cues (5.3% compared to 1% for VA trials; 5.6% compared to 1.7% for VH trials). Similarly, Sinnett, Spence & Soto-Faraco (2007) showed that when participants are presented with combined, but non-redundant visual-auditory stimulus, they often failed to report the auditory cue. With trimodal cues, Hecht and Reiner (2009) found that participants erred most often by responding to two, rather than only one of the three cues (5.5% compared to 1.3%, respectively). No modality bias was reported.

These results raise two major concerns, namely (1) that people may miss one or more signals when multimodal cues coincide with one-another (shown above) and (2) that one modality might dominate others when cues are presented concurrently. Our goal in this dissertation is therefore to establish how well people can process various combinations of concurrent non-redundant multimodal cues, including triplets, in the presence of a continuous visual/manual task, such as driving. As discussed earlier, answering this question is particularly important with respect to senior citizens, a segment of our population that will grow precipitously over the next few decades but that has been neglected in most multimodal studies to date.

An Aging Population

The United States Census Bureau reports that, in 2010, adults aged 65 years and older comprised 13% of the total U.S. population (40 million people; West, Cole, Goodkind & He, 2014). This percentage is expected to increase to 20.9% (84 million) by the year 2050, (see Figure 1.2). Even greater increases are expected for individuals 85 years and older; from 5.5 million in 2010 (1.8% of the U.S. population) to 18 million in 2050 (4.5%), Figure 1.3. The significant population growth in these age groups can be primarily attributed to (1) an increased life expectancy and (2) the aging of the baby boomer generation (Eby & Molnar, 2009; U.S. Census Bureau, 2008).

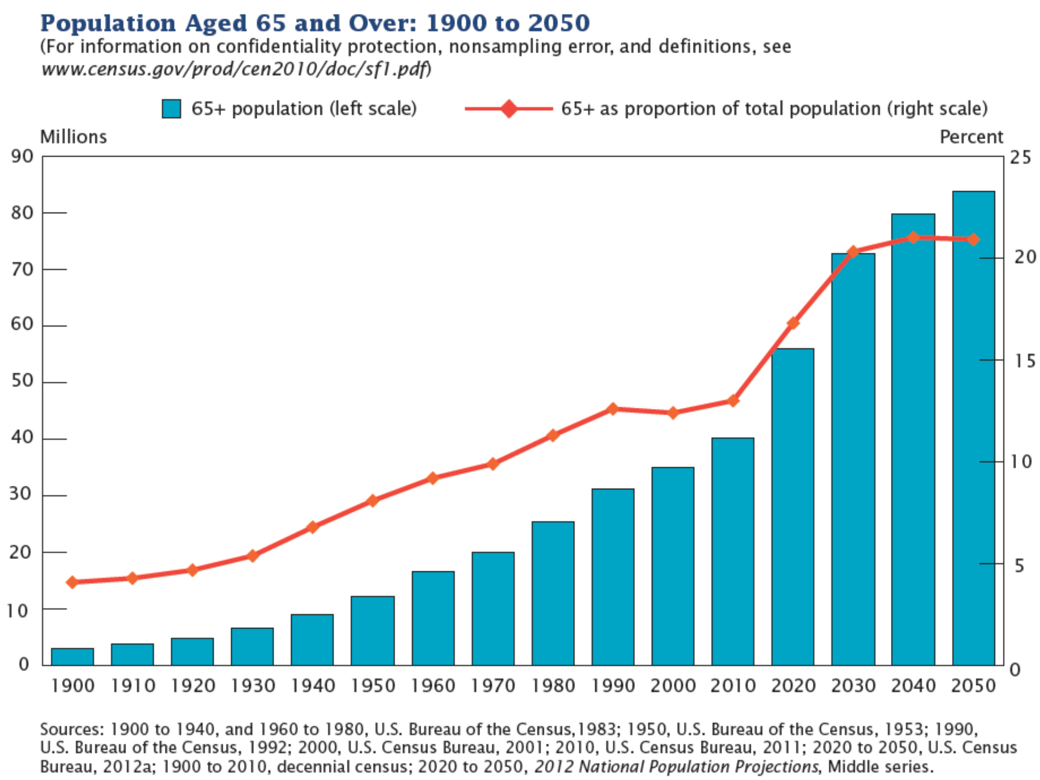

Figure 1.2 U.S. projections for adults 65 years and older (from 65+ in the United States: 2010 – West, Cole, Goodkind & He, 2014)

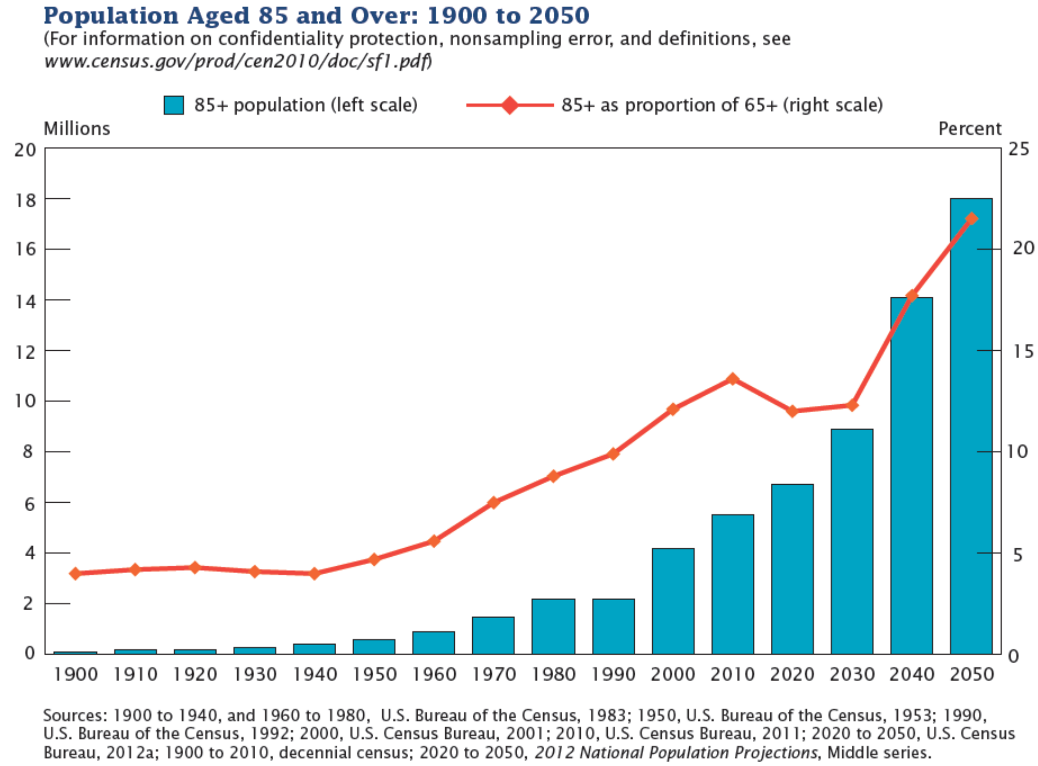

Figure 1.3 U.S. projections for adults 85 years and older (from 65+ in the United States: 2010 – West, Cole, Goodkind & He, 2014)

Older adults also represent the fastest-growing segment of the American workforce. People 55 years and older are forecast to make up one-fourth of the civilian labor force in 2020 (U.S. Census Bureau, 2008). At the same time, the percentage of older drivers (65 years and older) is estimated to increase from a current 15% to more than 25% by 2030 (Staplin et al. 2001). The ability to continue to work and drive provides a number of benefits to individuals in these age groups. It allows them to retire later which, in turn, enhances their cognitive and physical well-being, and also helps them sustain social participation without feelings of isolation (Liddle, McKenna, & Broome, 2004; Ragland, Satariano, & MacLeod, 2005), diminished self-worth (Alder & Rottunda, 2006; Kua, Korner-Bitensky, & Desrosiers, 2007) and low self-esteem (Dobbs & Dobbs, 1997). In other words, these activities afford elderly individuals the ability to maintain greater independence throughout later stages of life. Given the projected increase in this population, it will be critical that designers and engineers consider the older adult when developing new human-machine systems and associated interfaces. In doing so, we promote "aging-in-place," a concept that seeks to provide elderly individuals the ability to 'live in one's own home and community safely, independently, and comfortably regardless of age, income, or ability level' (e.g., Dishman, 2004; Mynatt, Essa, & Rogers, 2000; Mynatt, Melenhosrt, Fisk, & Rogers, 2004).

Many factors make aging non-homogenous, such as heredity, marital status, occupation, mental stimulation, physical activity/fitness, social engagement, and diet. Even within the same age group, there is large variation in mental and physical capabilities (Oakley, 2009). For example, a literature review on aging (Williams & Kemper, 2010) suggests that increased cognitive and physical activity is an intervention for preventing cognitive decline. However, very little research on aging has examined the effects that the above factors have on the ability to use and benefit from modern technology. It is therefore not clear whether older adults can cope with and will benefit from multisensory displays and interfaces given (1) the known decline in sensory abilities associated with aging, (2) difficulties with divided attention in older adults, and (3) the scarcity of data on multimodal information processing in the elderly.

Aging and Sensory Declines

Although the aging process varies considerably between individuals, visual, auditory, and tactile sensitivities generally decrease around age 65 (e.g., Kahn et al., 1977; Li & Lindenberger, 2002; Schieber, 2003; Spoendin & Schrott, 1989; Stuart-Hamilton, 2012). In particular, aging decreases the ability to perceive fine spatial detail (e.g., Owsley & Sloane, 1990; Sturr, Kline &

Taub, 1990), and it leads to a narrowing of the peripheral visual field. For example, Alian, McDonald, Ostroff, & Schneider (2004) compared the detection of visual targets by young (age 12-15 years), middle-aged (24-38 years), and older (60-75 years) participants. They found that older adults showed significantly slower response times than did young and middle-aged individuals. Also, Collins, Brown, & Bowman (1989) showed that younger adults were able to identify targets at eccentricities of up to 30.8 degrees, compared to only 22.8 degrees for older adults. In addition to difficulty detecting targets, elderly individuals have been observed to falsely report signals that are no longer present. This phenomenon is known as persistence, i.e., the sensation that a stimulus is still present even after the presentation of that stimulus has ceased (Hawthorn, 2000; McFarland, Warren, & Karis, 1958).

Detecting high frequency sounds and discriminating small changes in frequency or intensity of sound is another ability that declines with age (e.g., He, Dubno, & Mills, 1998; Humes, 1996 cited in Schieber, 2003). Auditory frequencies larger than 2500Hz are very difficult to perceive for older adults (Hawthorn, 2000). In terms of intensity, some studies suggest that absolute sensitivity decreases at a rate of 1 dB/year and 1.5 dB/year for adults 60+ and 80+ years of age, respectively (e.g., Brant & Fozard, 1990; Davis, Ostri, & Parving, 1991; Fozard, 1990). Elderly individuals have also been shown to display more difficulty in localizing sounds (e.g., Geldard, 1972; Schieber, 2003), as well as a reduced ability to ignore background noise (Fozard, 1990; Hawthorn, 2000). Herman, Warren, & Wagener (1977) explain this difficulty in localization to be a function of the timing between multiple signals as opposed to their intensities. Krever & Alberti (1990) add that distinguishing auditory targets may depend on the duration of signals, such that for older adults, signals presented for a shorter time period (e.g., 20 msec as opposed to 200 msec) can be easily missed.

Finally, relatively little is known about how the sense of touch, across various body segments, is affected by age. In general, the discrimination of small tactile impressions made to areas of the body, primarily the hand, is reduced with age (e.g., Cholewiak, Collins, & Brill, 2001; Stevens, 1992). Verillo (1980) demonstrated a progressive decrease in sensitivity to higher frequency tactile stimulation (between 100-700 Hz), but no changes at lower frequencies (25-40 Hz) in adults 65 years and older. Goble, Collins, & Cholewiak (1996) confirmed these findings in their experiment that examined frequencies between 10-400 Hz. In terms of temporal and pattern processing, older adults have been observed to take 2-5 times as long to notice vibrotactile patterns presented to their fingers, compared to their younger counterparts (Craig et al., 2010). For short duration (on the order of 25 msec) tactile signals, presented in isolation, sensory persistence has been observed in the elderly (Verrillo, 1982).

Decreased sensitivities have been shown to lead to more missed signals and longer reaction times (e.g., Bunce, MacDonald, & Hultsch, 2004). Promising ways to compensate for age-related deficits in vision include (1) providing 2-6 times more luminance contrast to increase the likelihood of object detection and recognition (Blackwell & Blackwell, 1971; 1980; Schieber, 2003), and (2) minimizing the need to have to work too closely to the eyes and the dependency on peripheral cues (Schieder, 2003). Other recommendations include avoiding cluttered displays, the use of short-duration signals that convey critical information, and small movements. These factors can reduce access costs and fatigue (Hawthorn, 2000). Overcoming auditory and tactile deficits can be achieved by increasing stimulus intensity, avoiding high-frequency signals (audition only), and using redundant auditory-visual or tactile-visual signals if targets need to be localized (Schieder, 2003).

Aging and Attention

The most widely studied forms of attention are selective, focused, and divided (Wickens, Lee, Liu, & Gordon-Becker, 1998). Selective attention refers the ability to choose particular inputs for conscious processing. Focused attention, on the other hand, involves suppressing unwanted or irrelevant cues and processing only relevant information. Divided attention, the one of greatest importance for this research, describes the ability to attend to multiple sources of information in parallel. In general, this form of attention is most relevant in complex, data-rich domains where operators are presented concurrently with many tasks and large amounts of data. It is also the one that has been shown to be most affected by aging (e.g., Craik & Salthouse, 2011; McDowd & Craik, 1988; McDowd, Vercruyssen, & Birren, 1991; Somberg & Salthouse, 1982; Verhaeghen & Cerella, 2002), especially for complex, as opposed to menial, tasks (Hawthorn, 2000).

In early work (Broadbent & Heron, 1962), older adults were asked to perform a series of number searching tasks in the visual modality, while being presented simultaneously with auditory streams that instructed participants to write down letters. Participants mostly ignored one task while maintaining performance on the other, without bias for either task. More recently, Tsang (1998) presented younger (20-39 years), middle-aged (40-59), and older (60-79) participants with 5 dual tasks in separate trials. For example, during one segment of the experiment, they performed a horizontal tracking task in combination with orientation discrimination, while during a different segment, they engaged in the tracking task in parallel with performing a memory task. This study found that timesharing performance significantly decreased as age increased, especially under conditions of intense attentional demands and when precise manual control of a joystick (in the tracking task) was required. Recent meta-analyses on aging and divided attention in the context of dual-task performance confirm the existence of age-related significant latency costs (Verhaeghen, Steitz, Sliwinski, & Cerella, 2003) and decreased accuracy (Verhaeghen & Cerella, 2002) on one or more tasks.

In applied settings, Ponds, Brouwer, & van Wolffelaar (1988) confirmed that, when younger and older adults engage in a driving task while performing a visual choice-reaction time task, older adults struggle significantly more with performing both tasks simultaneously. Specifically, detection performance on the visual task was nearly the same between the two age groups, roughly 85%. However, older adults maintained proper lane position only 70% of the total task time, compared to 87% for the younger participants. Similarly, in a comprehensive review of age-related deficits in sensory and cognitive function, Schieber (2003) cited a series of driving experiments conducted by Brouwer, Ickenroth, Ponds & van Wolffelaar (1990) that compared the lane keeping of older adults to that of their younger counterparts. In one study, they found that elderly individuals' performance suffered in the dual-task condition (when asked to drive and perform a visual search task), but improved by 50% once participants were instructed to provide verbal, as opposed to manual, responses – suggesting an advantage to offloading the motor channel (van Wolffelaar, Brouwer & Rotthengatter, 1991). Korteling (1994) investigated divided attention in older adults by asking participants to perform a steering and car-following task under two conditions: 'normal' – displacement of the accelerator pedal increased speed and 'inverted' – displacement of the accelerator pedal decreased speed. In this inverted condition, older drivers' attention was focused on the compensatory behavior required to complete the difficult operation, which affected the steering/lane keeping task only. The car following task, however, was not affected by the counterintuitive speed control.

As of means of improving performance and alleviating problems divided attention, some researchers have explored the use of a ‘variable priority’ strategy in which the priority assigned to each task in a dual-task paradigm alternates throughout an experiment (Gopher, Weil & Bareket, 1994). For example, if required to perform two simultaneous tasks, participants are instructed to focus primarily on one of the two tasks, while performing only minimal operations on the other. At some point, this prioritization is reversed and the task receiving less attention now becomes the primary task. This has been found to increase dual-task performance in older adults.

The above-mentioned limitations represent signs of normal aging. A related and more serious concern is a condition known as mild cognitive impairment (MCI) – the transitional stage between normal aging and a more critical loss in cognitive abilities (e.g., Feldman & Jacova, 2005; Gauthier et al. 2006). In particular, non-amnestic MCI describes impairments related to various non-memory functions such as attention (Loewenstein et al., 2007; Nelson & O’Connor, 2008; Petersen, 2004), the cognitive process of primary concern in this research. Currently, an estimated 3-19% of adults 65 years or older suffer from this condition (Gauthier et al. 2006), and with the older adult population growing rapidly, MCI may become a major concern in interface design. Since divided attention is of great importance for this work, participants were administered a Montreal Cognitive Assessment (MoCA; Nasreddine, Phillips, Bédirian, Charbonneau, Whitehead, Collin, Cummings, & Chertkow, 2005) that is able to detect early signs of the disease. This assessment was used to determine the eligibility of participants for the current research.

Multimodal Information Processing in Older Adults

The vast majority of studies on multimodal information processing to date have involved young participants (often students) only. The few experiments that have examined the effect of aging on multimodal information processing have done so mostly in the context of simple human-computer interaction tasks, such transferring files (Emery et al. 2003; Jacko et al. 2003, 2004; Lee, Poliakoff, & Spence, 2009; Oakley, 2009). For example, a dissertation compared the performance of younger and older adults on a task requiring moving a mouse from one target to another. As participants approached the destination, bi- and trimodal feedback was provided until the mouse pointer was correctly placed on the target. Visual-auditory redundancy led to the shortest movement time for younger adults, while combining redundant cues in all three modalities – vision, hearing, and touch – most benefited performance in older adults (Oakley, 2009).

Similarly, Emery et al. (2003) and Jacko et al. (2004) assessed the ability of older adults with varying levels of computer experience to perform a drag-and-drop task, while being provided with multimodal feedback about the placement of the computer file. In these studies, combined auditory and tactile cues led to significantly better performance (in terms of response time) than unimodal signals, regardless of experience level. More experienced users performed equally well in all bi- and trimodal feedback conditions. Lee, Poliakoff, & Spence (2009) confirmed the benefits of redundancy when they examined the performance of older participants (69-75 years of age) who had to divide their attention between a mobile phone task and a visual recognition task. They found that participants responded more quickly and accurately to redundant visual-auditory and visual-auditory-tactile cues, compared to visual or auditory signals in isolation. Performance did not differ between the bi- and trimodal conditions, which were rated as less difficult by participants in a debriefing session. Overall, these studies suggest that combining redundant cues in two modalities enhances performance for elderly individuals, thus compensating for deficits in individual channels (Mahoney, Verghese, Dumas, Wang, & Holtzer, 2012). Response times for tri-and bi-modal combinations are almost always shorter than for individual, unimodal cues. However, no significant differences were observed between any of the bimodal (i.e., visual-auditory, visual-tactile, or auditory-tactile) combinations, nor between bimodal and trimodal cue pairings.

It is important to note that most of the above experiments were performed using rather simple tasks, and the generalizability of their findings to more cognitively demanding tasks and data- rich environments is unclear.

Perceptual and Attentional Processing Limitations

As highlighted by Hecht & Reiner (2009), the occasional failure of people to notice signals when they are presented concurrently in different modalities can limit the effectiveness of multimodal displays. This observation warrants the development of countermeasures which requires a thorough understanding of the relative benefits and limitations of, as well as the possible linkages and interference between different sensory channels (e.g., Giang et al., 2010; Lu et al., 2013; Spence & Driver, 1997b).

One important phenomenon that needs to be considered in multimodal display design is the visual dominance effect, or the tendency of participants to respond predominantly to the visual component of a bimodal stimulus (Colavita, 1974; Posner, Nissen, & Klein, 1976). This effect has been observed mainly for visual-auditory (Sinnett, Spence, & Soto-Faraco, 2007; Ward, 1994) and visual-tactile (Hecht & Reiner, 2009) modality pairs. Psychophysicists debate whether the sensory dominance phenomenon is due to 'wiring' of the senses or attentional allocation as a result of expectation and frequent exposure to visual stimuli (Posner, Nissen, & Klein, 1976).

Another important factor is forward and backward masking which occur when a target stimulus is corrupted by a preceding (or subsequent in the backward condition) masking stimulus (Craig & Evans, 1987; Giang et al. 2010). For example, a tactile signal might be masked by an auditory cue if the tactile cue is presented in too short of a time period after the auditory one. This phenomenon has been generally observed for short duration signals, on the order of 50 msec, and results in missing the first (backward) or second (forward) signal in a stimulus pair.

Crossmodal links in attention represent yet another factor that affects the effectiveness of multimodal designs. Specifically, one indication that modalities are not entirely independent of each other is so-called modality expectations, i.e., the readiness of an observer to respond to a signal or event in a modality in which he or she expects a signal to appear (Spence, Nicholls, & Driver, 2001; Spence, Pavani, & Driver, 2000). Crossmodal spatial and temporal links in attention also need to be considered (e.g., Ferris & Sarter, 2008; Spence, Pavani, & Driver, 2000; Spence & Driver, 1997). Crossmodal spatial links refer to the fact that, if information is presented in one modality in a particular location, this leads to an increased readiness to perceive information in other modalities in the same or similar location. On the other hand, crossmodal temporal links can take the form of (1) crossmodal attentional blink and (2) crossmodal inhibition of return. A crossmodal attentional blink is experienced when the second of two signals is missed because they are presented in too close temporal proximity of one-another (e.g., 50-200 msec for visual-auditory stimulus; Arnell & Jolicoeur, 1999; Martens & Johnson, 2005; Wickens & Hollands, 2000; up to 450 msec for visual-tactile stimulus; Soto-Faraco, Spence, Fairbank, Kingstone, Hillstrom, 2002). Crossmodal inhibition of return (IOR), on the other hand, refers to an orientation mechanism that briefly enhances (for approximately 100-300 msec) the speed and accuracy with which an object is detected after the object is attended, but then impairs detection speed and accuracy (for approximately 500-3000 msec; Klein, 2000; Spence & Driver, 1988).

Context-Sensitive Displays: Countermeasures to Missed Signals

The above-mentioned processing phenomena and limitations, in combination with aging, are likely to lead to missed information and/or longer response/reaction times. One promising countermeasure to these performance breakdowns is context-sensitive display design where the timing, salience, amount, modality, location, or frequency of signals may be adjusted to account for changing needs and demands (such as different users or cue combinations; Kirlik, 1993; Parasuraman, Bahri, Deaton, Morrison, & Barnes, 1992; Parasuraman, Cosenzo, & Visser, 2009).

Context-sensitive designs can take one of two forms: (1) adaptive displays and (2) adaptable displays. In adaptive displays, the system is responsible for adjusting signal parameters based on monitoring the operator’s attentional state (using, for example, physiological measures, such as heart rate or eye movement data) and performance, and adjusting information presentation in response to observed breakdowns. One advantage of adaptive displays is that adjustments are being made without imposing additional interface management tasks on the operator (Hameed & Sarter, 2009). However, one shortcoming of this approach is the potential for reduced situation and system awareness on the part of the user (Wickens, 1994). Adaptable displays, on the other hand, are those in which the human operator is given the authority to change parameters based on his/her needs, preferences, evaluation of the system's status, context, and cognitive state (Hameed & Sarter, 2009; Kirlik, 1993). The greatest advantage of this approach to context-sensitive display design is that the operator is in control and thus more likely aware of display settings at all times. The drawback, here, is that the display adjustments are most often needed, and require operator attention during times when attentional resources are already consumed by other tasks (e.g., Miller, Funk, Goldman, Meisner, & Wu, 2005). During the final stage of this research, we will evaluate the effectiveness and feasibility of one particular implementation of an adaptive multimodal display.

Crossmodal Matching: A Critical but Neglected Step in Multimodal Research

Before we conduct studies to examine the above issues, we need to address a major methodological shortcoming of most multimodal research: the failure to perform crossmodal matching. Crossmodal matching refers to the process of an "observer matching the apparent intensities of stimuli across two sensory modalities" (Bryant, 1986; Colman, 2015; Marks, 1988; Von Wright, 1970), such as equating the brightness of a light to the loudness of a sound or to the intensity of a vibrotactile signal. Performing this step in advance of an experiment is critical for ensuring that observed performance differences can indeed be attributed to modality per se, i.e., that modality is not confounded with other signal properties (Gescheider, 1988). For example, a study may compare the response time to visual, auditory, and tactile cues and find that participants responded faster to tactile cues compared to visual and auditory ones. Unless crossmodal matching was performed prior to the experiment, it is impossible to tell whether the results are due to inherent properties of the sensory channels (e.g., different conduction velocities) or whether the intensity of the tactile stimulus was simply greater than that of the other signals. Crossmodal matching is necessary also because of the considerable between-subject variability observed with respect to perceived stimulus intensities in different sensory channels (Stevens, 1959). It helps determine the proper crossmodal matches for each individual study participant. For the current study, this step will be especially critical given the large differences in ages and the potential for various declines in sensory channels.

Early psychophysical studies that employed crossmodal matching did not all use the same method. In a seminal crossmodal matching experiment, Stevens (1959) employed the method of bracketing, or turning the levels of stimuli, such as loudness (20-90 dB) and vibration amplitude (10-50 dB), alternatively too high or too low, in order to “zero in” on equality, without allowing participants to see the dial on the stimulus control. Galinsky et al. (1990) adapted a similar method of bracketing for matching the apparent loudness of noise to the apparent brightness of a visual stimulus. In this study, there was no mention of whether feedback (in any form) was available to participants. In contrast, Brill et al. (2007, 2008) asked participants to match successively the apparent loudness of auditory and tactile stimuli to that of a visual stimulus. In these particular studies, matching was performed in only one direction, but not in reverse (e.g. matching from vision to audition or from touch to audition). Also, in some cases, matching was performed only once per modality pair. It is not clear how reliable and consistent participants’ choices would be if matches were repeated and performed in both directions.

Given this lack of an agreed-upon method and the limitations associated with these early crossmodal matching techniques, we conducted a review of publications in the applied human factors and ergonomics literature from 1994-2014. The goal of this review was to identify the most common procedures used. Our survey of the literature revealed that crossmodal matching was reported for only 2.6% (4/152) of studies on multimodal information presentation.

In addition, crossmodal matching was mentioned in 7 Proceedings papers that were published during the same time period. Nine of these 11 papers provided rather limited descriptions of how the procedure was performed (e.g., “participants performed a crossmodal matching procedure to equate the intensity of a light to the loudness of a sound”) and did not report the results of the matching task. An additional 7 articles (not counted in the 11 papers) identified during the search acknowledge psychophysical concerns (such as, “all cues were amply above threshold to account for saliency concerns” or “no specific attempt was made to match the intensities of the stimuli, which were clearly suprathreshold”) as a substitute for performing the task.

Table 1.1 summarizes the available information about the techniques employed in the 11 studies. In the table below, ‘–‘ denotes missing information; ‘alternating stimuli’ = whether matches between stimuli in two different modalities were performed in both directions; ‘feedback type’ = whether and what type of information was presented to participants regarding their match values; ‘input mechanism’ = the type of control that was used to vary intensity of the matching stimulus; ‘repeated matches’ = the number of times the same match was repeated; ‘type of judgment’ = how the cues were compared to one-another (absolute – judgment about a single stimulus – or relative – judgment about a stimulus is made relation to a reference stimulus); ‘participants’ = if participants that performed the task were the same as those in the actual experiment; Shaded articles are journal publications and the remaining are Proceedings papers.

Table 1.1 highlights the scarcity of studies and publications that perform or report crossmodal matching and the lack of consistency among the reported techniques. It raises questions about the validity of the various approaches and makes comparing results across studies difficult.

Table 1.1 Studies employing crossmodal matching between the years of 1994-2014

Alternating Stimuli	Feedback Type	Input Mechanism	Repeated Matches	Type of Judgement	Participants	Reference
–	–	Knobs	Yes	Relative	Different	Ngo & Spence, 2010
No	Visual	Keyboard	10 times	–	Same	Orchard-Mills et al., 2013
No	–	–	4 times	Relative	Different	Ortega et al., 2014
–	–	–	–	–	Same	Szalma et al., 2004
Yes	–	–	–	–	Same	Brill et al., 2007
Yes	–	–	–	–	Same	Brill et al., 2008
Yes	–	–	–	–	Same	Brill et al., 2009
–	Visual	Sliding scale	–	Relative	Same	Garcia et al., 2009
–	–	–	–	–	–	Scerra & Brill, 2012
–	–	–	–	–	–	Shaw, 2006
–	–	–	–	–	–	Terrence & Brill, 2005

For example, given the potentially large intra-individual variability of crossmodal matches (Teghtsoonian & Teghtsoonian, 1983), it is likely not sufficient to obtain a single match value – for a given modality pair – from each person. Also, crossmodal matches may be affected by the order of presentation of the two stimuli and/or the input mechanism and feedback provided while performing the task.

In summary, crossmodal matching is a critical but often neglected step in research on multimodal information processing. Currently, no agreed-upon method exists for ensuring that modality is not confounded with other important signal characteristics. The first phase of the proposed research will therefore seek to fill this gap by comparing the effectiveness and feasibility of various candidate crossmodal matching procedures.

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CHAPTER 2

Crossmodal Matching: A Comparison of Three Techniques

As discussed in the Introduction, crossmodal matching is a critical step for ensuring that modality is not confounded with other signal properties, such as salience (e.g., Bryant, 1986; Colman, 2015; Gescheider, 1988; Marks, 1988); yet, an estimated 95% of studies on multisensory information processing fail to perform this step. Given this shortcoming of most multimodal experiments and the lack of an agreed-upon crossmodal matching technique in the literature, the purpose of this first step in our line of research was twofold: (1) we sought to determine whether different matching techniques result in the same or comparable levels of within-subject variability, i.e., and (2) we wanted to identify the most reliable (i.e., lowest within-subject variability) and efficient technique to be used in subsequent stages of this dissertation.

The study reported in this chapter compares the outcome of three different crossmodal matching techniques for the same visual-auditory, visual-tactile, and auditory-tactile stimuli pairs. The three techniques differed with respect to the controls used to adjust stimulus intensities and the associated feedback on match values. In particular, a sliding scale and computer mouse, computer keyboard arrows, and a rotary knob (encoder) were used as means of adjusting stimulus intensity. These techniques were employed for a number of reasons. First, the sliding scale/mouse and rotary knob designs had been used in prior studies (e.g., Ngo & Spence, 2010;

Garcia et al., 2009). Also, each of these techniques supports different levels of precision in terms of intensity adjustments, such as larger rapid (e.g., rotary knob) vs. gradual (e.g., keyboard) changes, and thus different gains. Finally, the computer mouse/sliding scale technique involved visual feedback about match values. Our concern was that this might facilitate anchoring, i.e., remembering and using an earlier match to make subsequent judgments. Therefore, the keyboard arrow and the rotary knob designs eliminated visual feedback/anchors. Our goal was to compare the three approaches in terms of their efficiency and within-subject variability. To this end, we employed multiple match trials – in both directions (e.g., visual-to-auditory and auditory-to-visual) – for the above three stimuli pairs. Similar to the 11 studies listed in Table 1.1 (chapter 1), the experiment used the method of adjustments, where the experimenter sets the intensity of one stimulus and the participant is then asked to adjust the intensity of the to-be-matched stimulus until the two are perceived to be equal. Using this method helps avoid experimenter interference and does not constrain participants' choices, i.e., does not force them to select approximate as opposed to exact values.

Methods

Participants

Eighteen University of Michigan undergraduate and graduate students volunteered to participate in the experiment (10 males and 8 females; mean age = 24.2 years, SD = 3.1). They reported normal to corrected-to-normal vision, no hearing impairments, and no compromised sense of touch. The 18 students were randomly assigned to one of three experimental groups (sliding scale and mouse, keyboard arrows, or rotary knob), containing 6 participants each. The groups did not differ significantly with respect to age.

Multimodal stimuli and apparatus

The visual stimulus consisted of a blue light-emitting diode (LED), covered by a standard-sized table tennis ball (to increase the size and visibility of the light), with a luminance range of 0-126.77 cd/m^2. The light was located in the participant's peripheral vision, at an angle of approximately 35 degrees (10.5 inches) below the center of a 19" computer monitor on which the matching task was presented (Figure 1). Auditory cues were 350-Hz monotone beeps transmitted via stereo headphones, with a loudness range of 0-88 dB. Tactile cues were vibrations presented at 250 Hz (Jones & Sarter, 2008), using a single C-2 "tactor" (commercially available piezo-buzzers inside a 1" x 1/2" x 1/4" plastic casing; by Engineering Acoustics Inc.). The tactile signal gain ranged from 0-18 dB (the maximum gain of C-2 tactors). The tactor was attached to the front/middle of a Velcro belt fastened around participants' waist, over clothing (i.e., Scott & Gray, 2008), and was in direct contact with the skin. The choice and location of these three stimuli was driven by their intended use in a subsequent driving simulation (as shown in Figure 2.1). Pink noise was played over the stereo headphones to eliminate any audible sounds associated with the tactor vibrations. Overhead room lighting was turned off during this experiment.

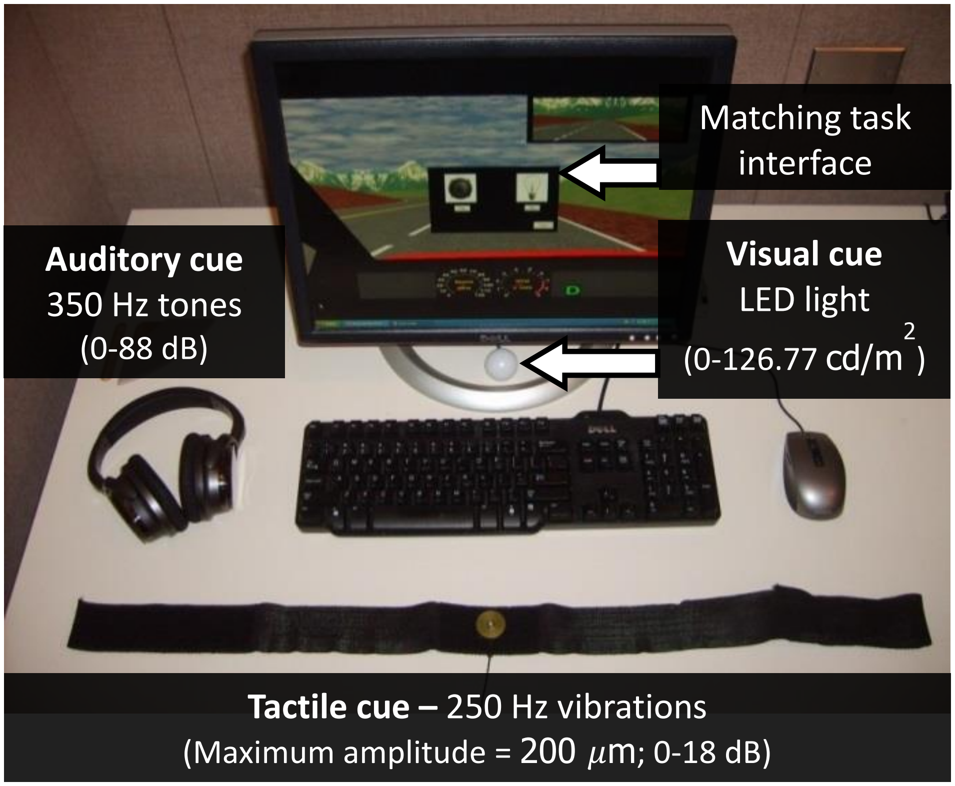


Figure 2.1: Crossmodal matching task experimental setup

Crossmodal matching task

Participants performed a series of crossmodal matching tasks, using the interface shown in Figure 2.2. In each case, they were presented with two cues in different modalities (e.g., tactile and visual, as seen in Figure 2.2). The frequency and intensity of the first ‘reference’ cue, represented by the image on the left side of the interface, were set by the experimenter. For the second ‘variable’ cue, shown on the right side, only frequency was fixed. Participants were instructed to “adjust the variable cue until you feel that its intensity is equal to that of the reference cue.” The intensity of the visual, auditory, and tactile cues was measured in terms of luminance, loudness, and gain/amplitude, respectively.

For each trial, the ‘play’ button below the left image was used by participants to initiate a one-second presentation of the reference cue which could be repeated as often as desired. The ‘play’ button below the right image was used to activate the variable cue, which then played continuously. One-third of the participants (sliding scale and mouse technique – “visual feedback” condition) used the computer mouse to move the sliding scale at the bottom in order to adjust the intensity of the variable cue until it matched that of the reference cue (intensity increased from left to right; Figure 2.2).

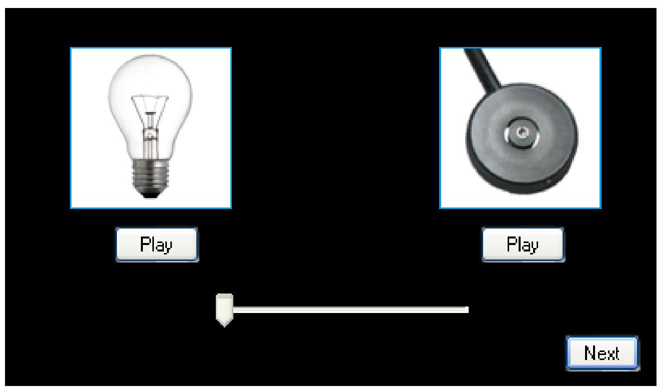


Figure 2.2: Matching task interface for visual feedback condition (The sliding scale was not visible in the keyboard arrows and rotary knob techniques)

Another third of participants (keyboard arrows technique – “no visual feedback” condition) used the left and right arrows on the computer keyboard for the same purpose. The remaining third of participants (rotary knob technique – “no visual feedback” condition) used a rotary encoder hardware knob to adjust intensity (which increased with a clockwise turn of the knob), Figure 2.3. Once participants were satisfied with their choice of match value, the ‘next’ button on the interface (for the sliding scale and mouse technique) or the ‘enter’ key on the keyboard (for the keyboard arrows and rotary knob techniques) was used to proceed to the subsequent matching task. Participants were not limited in terms of the amount of time they could spend adjusting the intensity of cues. They were informed that each match was independent.

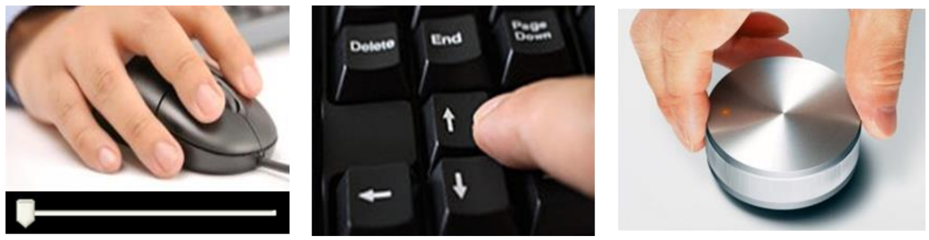


Figure 2.3: Input mechanisms for each matching task technique: sliding scale and mouse (left), keyboard arrows (middle), and rotary knob (right)

[Sources: http://anderscpa.com/anders-named-a-firm-to-watch-2/; http://www.alamy.com/stock-photo-finger-pressing-up-arrow-button-on-black-keyboard-11602435.html; http://uxd-trend.tistory.com/9]

Experimental design and procedure

The experiment employed a 6 (match type: visual-auditory, auditory-visual, visual-tactile, tactile-visual, auditory-tactile, and tactile-auditory) x 3 (experimentally set reference cue intensity: 20, 50, and 80) x 3 (matching technique: sliding scale/mouse, keyboard arrows, and rotary knob) mixed full factorial design. Match type and reference cue intensity were within-subject variables, while matching technique was a between-subject variable. For analysis purposes, the range of intensities for the visual, auditory, and tactile stimuli was normalized on a scale from 0 to 100 (0 being the off position and 100 being the maximum intensity of the equipment). The reference cue intensity for each modality were set at 20 (low intensity), 50 (medium intensity), and 80 (high intensity). Participants repeated each match 3 times for a total of 54 matching tasks. The order in which various matches were presented was counterbalanced.

The experiment lasted approximately 30 minutes. Prior to the experiment, and without time constraints, participants explored the full spectrum of possible intensity values for each of the visual, auditory, and tactile modalities.

Results

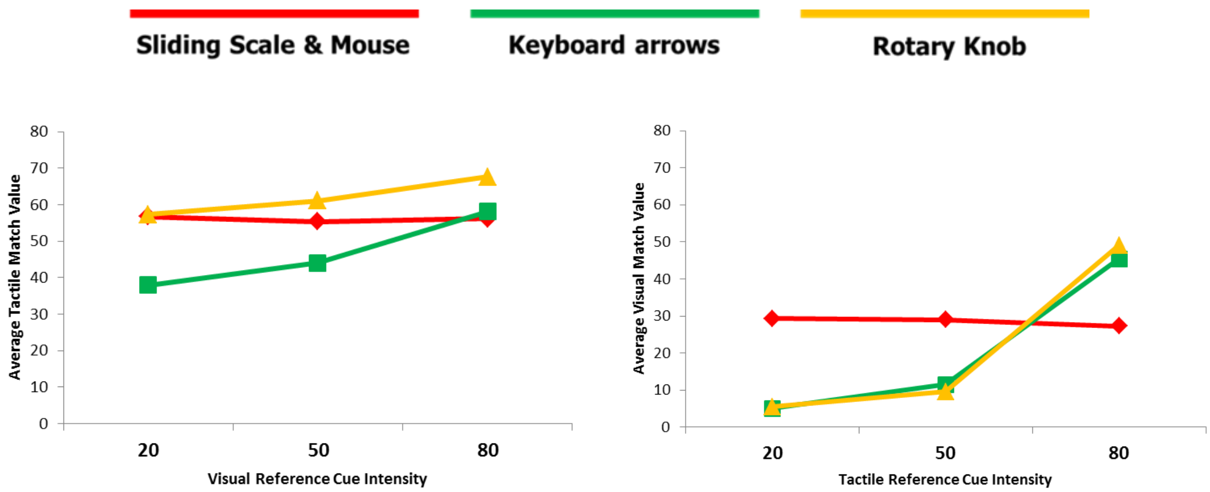
The dependent measure was the intensity values for the variable cues. As a first step, crossmodal matching functions (Stevens, 1959; 1966) were created to display the reference stimulus as a function of the to-be-matched (variable) stimulus. The main reason for this analysis was to validate and verify that participants were able discriminate differences in sensations produced by the stimuli. A second reason was to compare our findings with previous studies that focused on the psychophysical matching relationship between modalities.

Next, we focused our analysis on the within-subject, or intra-individual, variability of participant's three matches for all modality pairs as large variations represent a major concern for studies that employ no crossmodal matching or that use a single match. To this end, we calculated residual values by subtracting individual match values from the average variable intensity for each reference cue intensity and match type. The absolute value of residuals was used in the subsequent analysis. For example, if a person selected 35, 45, and 50 as the visual match values (which correspond to 44.4, 57.0, and 63.4 cd/m^2 in brightness intensity) for a tactile reference cue of 50, the mean visual match value would be 43.3 (or 54.9 cd/m^2). The three corresponding residuals used for the data analysis would be 8.3 (|43.3 - 35|), 1.7 (|43.3 - 45|), and 6.7 (|43.3 - 50|). Residuals of all participants, in each condition, were then combined for each reference intensity and match type, to be considered as a group. A high residual average meant that participants' matches showed a large degree of variability. A case with no variability would have resulted in a residual average of zero.

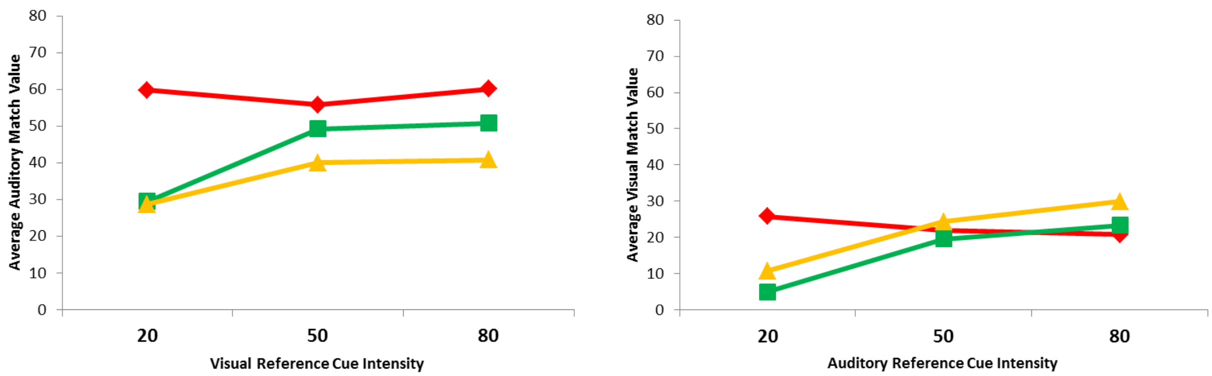
A mixed-model repeated measures analysis of variance (ANOVA) was used to identify main and interaction effects. Two-tailed Fisher's LSD post-hoc tests and paired comparisons were performed to determine differences between means for significant effects. Bonferroni adjustments were applied for multiple statistical tests. Significance was set at $p < 0.05$.

Crossmodal matching functions

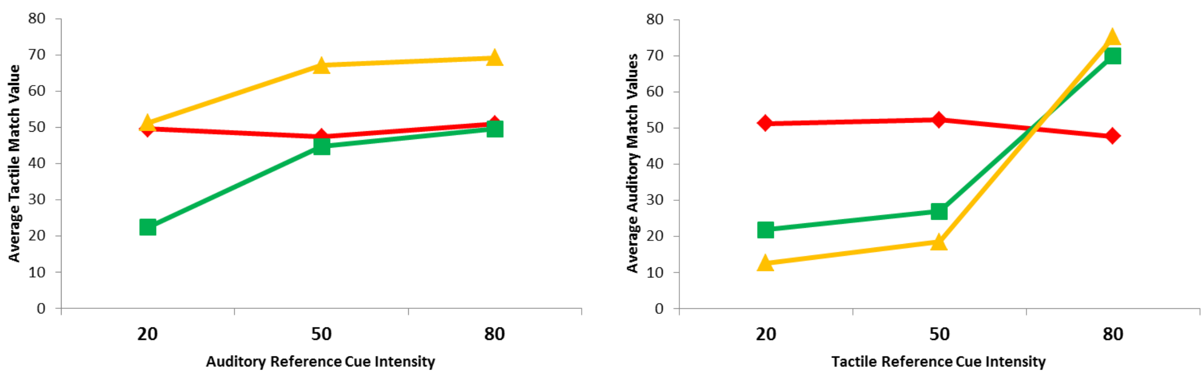
In the graphs below, the crossmodal matching functions for both the keyboard arrows (green) and rotary knob (yellow) techniques emulate the same behavior regardless of the specific match type, that is, some form of a polynomial, exponential, or logarithmic relationship. This trend was observed even though in some cases the average magnitude estimation between the two methods was not the same. In particular for these procedures, matching that involved a tactile reference stimulus resulted in the most well-defined, and closely overlapping, curves as opposed to when touch needed to be adjusted. On the other hand, functions for matches between vision and audition did not display as distinctive tendencies. Overall, the sliding scale and mouse technique (red), compared to the other two, showed no consistent pattern. The relationship between the reference intensity and the to-be-matched stimulus appeared much less defined (more constant) for nearly all modality pairings.



(A) Visual-Tactile (left) and Tactile-Visual (right) matches



(B) Visual-Auditory (left) and Auditory-Visual (right) matches



(C) Auditory-Tactile (left) and Tactile-Auditory (right) matches

Figure 2.4: Crossmodal matching functions (reference stimulus as a function of the variable stimulus) for each technique, match type, and reference cue intensity

Comparison across three techniques

There was a significant main effect of matching technique ($F(2, 15) = 43.39$, $p < 0.001$). Residual values were significantly higher for the sliding scale and mouse technique (mean = 15.0), compared to the keyboard arrows (mean = 5.9; $p < 0.001$) and the rotary knob (mean = 7.8; $p < 0.001$) methods. Residual values for the keyboard arrows and rotary knob techniques did not differ significantly. There was also a main effect of match type ($F(5, 11) = 5.25$, $p = 0.01$). Residual values were higher for matches involving touch compared to those that did not. No other main effects or interactions were found.

Sliding scale and mouse. For the sliding scale and mouse technique, paired comparisons showed that, at all three reference cue intensities (20, 50 and 80), the residual values for tactile (reference)-visual (variable) (T-V) matches were significantly higher than for visual-tactile (V-T) matches (mean = 25.4 and 8.6 ($p = 0.001$), 24.4 and 9.3 ($p = 0.001$), and 23.7 and 6.9 ($p < 0.001$), respectively), Figure 2.5. Similarly, tactile-auditory (T-A) match residuals were significantly higher than for auditory-tactile (A-T), at all three reference cue intensities (mean = 23.8 and 12.0 ($p = 0.02$), 17.6 and 8.9 ($p = 0.010$), and 24.7 and 11.5 ($p = 0.009$), respectively).

Keyboard arrows. For the keyboard arrows technique, at a reference cue intensity of 20, residual values were significantly higher for V-T matches than for T-V matches (mean = 8.4 and 1.6, respectively; $p = 0.046$), Figure 2.6. For the auditory-visual (A-V) matches, residuals at a reference cue of 80 were higher than at 20 (mean = 7.2 and 1.6, respectively; $p = 0.025$). Also, at the 20 and 50 reference cue intensities, residuals for visual-auditory (V-A) matches were significantly higher than for A-V matches (at 20: mean = 10.3 and 1.9 ($p = 0.003$) and at 50:

mean = 9.3 and 3.2 (p = 0.036). No differences were found for matches involving auditory and tactile stimuli.

Rotary knob. For the rotary knob technique, paired comparisons showed that, at the 20 and 50 reference cue intensities, residuals for V-T matches were significantly higher than for T-V matches (at 20: mean = 10.3 and 1.9 (p = 0.025) and at 50: mean = 9.3 and 3.2 (p = 0.008), Figure 2.7. Also, for the visual-auditory (V-A) matches, residuals at a reference cue of 80 were higher than at 50 (mean = 11.3 and 7.8, respectively; p = 0.025). No significant differences were found for matches involving auditory and tactile stimuli.

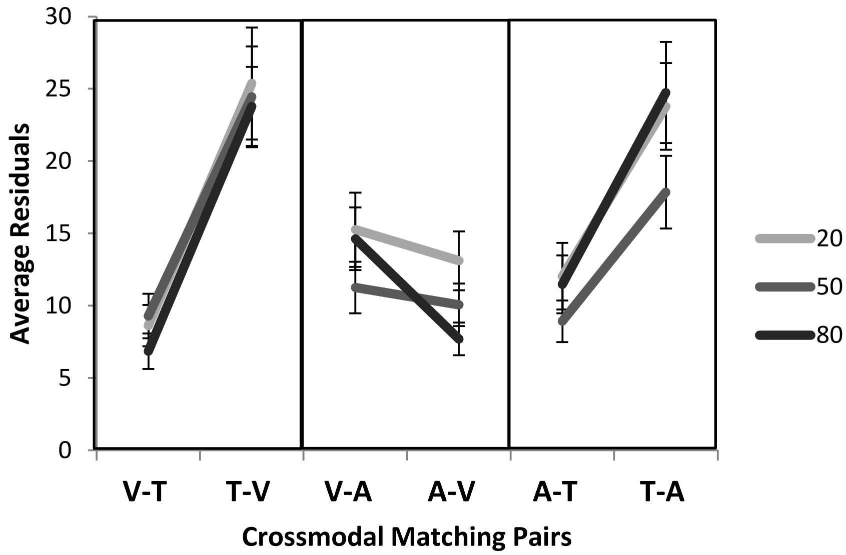


Figure 2.5: Average residuals for sliding scale and mouse technique for each match type and reference cue intensity

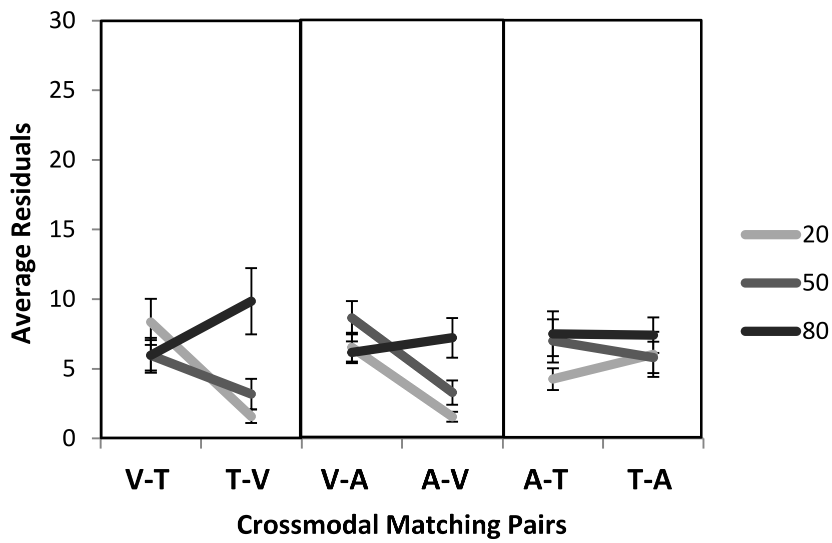


Figure 2.6: Average residuals for keyboard arrows technique for each match type and reference cue intensity

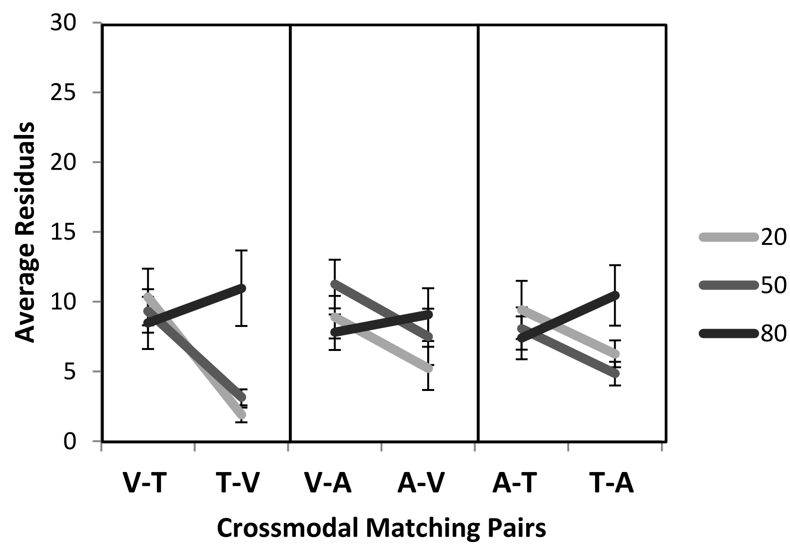


Figure 2.7: Average residuals for rotary knob technique for each match type and reference cue intensity

Discussion and Conclusion

Crossmodal matching is a critical first step in studies on multimodal information processing and display design. It helps avoid that modality is confounded with other signal properties and ensures that participants experience comparable stimuli. Yet, more than an estimated 95% of multisensory research fails to perform (or report) this step, and no agreed-upon crossmodal matching technique exists. The goal of this study was to determine whether three variations of the same basic method of adjustments produce the same crossmodal match values and comparable levels of intra-individual variability of matches.

All three techniques resulted in high between-subject variability of matches, confirming the need for each study participant to select their own set of crossmodal intensity values. More importantly, the high within-subject variability observed in this study highlights that it is not sufficient to obtain one match value for each match pair and participant. Figure 2.8 below shows the between- and within-subject variability for a tactile-auditory match for each of the three techniques and reference intensities.

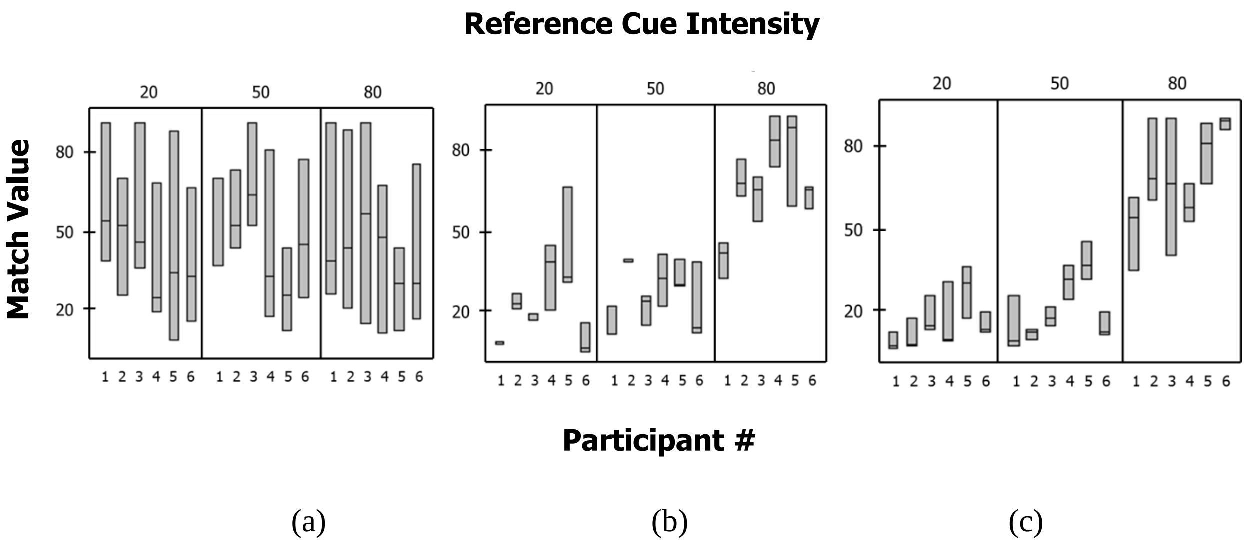


Figure 2.8: Tactile-auditory match: Range of three match values selected by each of six participants for each reference intensity and each technique: (a) sliding scale and mouse, (b) keyboard arrows, and (c) rotary knob techniques (each horizontal bar in the plots represents one of the three repeated matches)

Overall, the crossmodality matching functions revealed that participants were indeed able to discriminate between intensity values for each modality pairing when using the keyboard arrows and rotary knob techniques, which showed non-linear relationships in all cases. This trend, which resembled polynomial, exponential, or logarithmic functions, was most pronounced for tactile-auditory pairs, suggesting that changes in the tactile stimuli were the easiest to perceive. Previous work reported a linear relationship between audition and touch and also between audition and brightness (Stevens, 1959; 1966). The differences between our findings and prior work may be attributed to the fact that previous experiments employed larger intensity ranges than the current study (e.g., 10-50 dB compared to 0-18 dB in our study) and also tested more than three reference levels within these ranges.

In the present study, the technique used to perform crossmodal matching significantly affected within-subject variability. In particular, the sliding scale and mouse technique – which provided visual feedback on the match value via a pointer on the scale – led to higher residual values compared to the keyboard arrows and the rotary knob methods. The effect was most pronounced for matches involving a tactile reference cue. This result, in combination with comments provided by participants during a debriefing session, suggest that, in this condition, they were trying – but likely failed – to remember the slider position for previous matches, rather than making selections based on their actual perceptual experience in each instance. No significant differences were found between the keyboard arrows and the rotary knob techniques, neither of which contained visual feedback.

Overall, residuals were the lowest for the keyboard arrows method. One possible explanation for this finding is that, in this condition, stimulus intensity adjustments were made in a discrete fashion (i.e., through small incremental steps towards the appropriate match value) while they were continuous (i.e., affording rapid intensity changes at once and thus potentially requiring more corrections in either direction) for the mouse/sliding scale and rotary knob methods.

To some extent, the order of presentation of stimuli also affected within-subject variability for all techniques. In particular, residual values were significantly higher for the sliding scale and mouse method in cases where the reference cue was tactile. This was the case regardless of the initial reference cue intensity. One proposed explanation for this finding is the longer duration of tactile (haptic) sensory memory (~ 5-10 seconds), compared to visual (iconic, ~300-500 milliseconds), and auditory (echoic, ~3-4 seconds) memory (Colheart, 1980; Gilson & Baddeley, 1969; Sperling, 1960). For example, participants may have replayed the tactile reference stimuli less often than the visual and auditory ones, and instead relied more on memory than actual perception and relative judgments.

In conclusion, our findings of large between-subject variability in matches confirm the need for developing and employing a valid and reliable crossmodal matching technique prior to experiments on multimodal information processing. A key finding of this work is that even minor variations in methods can result in significant differences in match values and intra-individual variability. Additional research is needed to fine-tune the implementation of crossmodal matching techniques. In particular, it will be important to determine the number of repeats of the same match needed that would lead to convergence and ultimately reduce variations to determine the crossmodal match value to be used in an experiment. The keyboard arrows technique appears most promising and, for the purposes of this dissertation, will be employed in the remaining phases. In particular, the visual-tactile (V-T), auditory-visual (A-V), and tactile-auditory (T-A) match types were selected as the final matching pairs, and each reference stimulus intensity will be set at 50% of its total intensity because in most cases, residuals values were the lowest at this intensity level. However, participants will be asked to repeat each match 5, instead of 3, times to account for high within-subject variability. Another reason for employing crossmodal matching is the wide range of ages used in the following experiments. Our goal is to ensure that all participants can reliably perceive the stimuli.

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CHAPTER 3

Age-Related Differences in Detecting Concurrent Visual, Auditory, and Tactile Cues

Benefits of multimodal displays (i.e., displays that present information in vision, hearing, and touch), such as increased bandwidth and multitasking, have been highlighted by numerous studies (e.g., Calvert, Spence, & Stein, 2004; Sarter, 2006; Wickens, 2008). Many human-machine interfaces now integrate information in different modalities, previewed in the Introduction. However, little is known about limitations of this approach to information presentation. Several studies have shown that people are capable of processing two concurrent signals in different sensory channels, such as visual and auditory, very effectively without significant performance decrements (e.g., Ho, Tan, & Spence, 2005; Mohebbi, Gray, & Tan, 2009; Sklar & Sarter, 1999; Scott & Gray, 2008). However, to date, no systematic empirical data exist on the performance costs associated with the presentation and processing of more than two simultaneous cues in vision, hearing and/or touch (in particular) when these cues refer to different events. Also, it is not known how aging moderates the ability to process multiple concurrent multimodal cues. Answering the latter question is important given the fact that adults over 65 years of age are the fastest growing segment of our population and are known to suffer from a decline in sensory abilities (e.g., Li & Lindenberger, 2002; Stuart-Hamilton, 2012) and experience difficulties with divided attention (Somberg & Salthouse, 1982; Verhaeghen &

Cerella, 2002). The only study to date that investigated the processing of non-redundant, multimodal signals (Hecht & Reiner, 2009) reported breakdowns in detection performance when two or more cues were presented in parallel. However, this study involved younger participants (students) only.

Therefore, the main goals of the present study are to (1) establish whether people can reliably perceive and process more than two non-redundant cues that appear concurrently in visual, auditory, and tactile form and (2) investigate how aging modulates this ability. Also, this experiment will explore whether one modality is consistently detected or missed more often than others (e.g., Colavita, 1974). Based on the findings of Hecht & Reiner (2009) and attentional resource limitations described by Wickens & Hollands (2000), our expectations were that performance (detection rate and response time) will suffer significantly if a person is asked to notice and report 3 (as compared to 2) simultaneous multimodal signals and that this performance decrement will be more pronounced in older participants (e.g., Alian et al., 2004; McDowd, Vercruyssen, & Birren, 1991; Hecht & Reiner, 2009). The findings from this study will help identify limitations of multimodal information processing and may suggest countermeasures to ensure the robustness of multimodal displays.

Methods

Participants

Thirty-six participants volunteered to take part in this experiment. They were evenly divided into three age groups: 12 younger adults (19-27 years), 12 older working adults (65-78 years), and 12 older retired adults (65-72 years). Participants in the younger adult category were students at the University of Michigan (UM). Older adult participants, in both groups, were citizens of Ann Arbor and surrounding areas. Half of these individuals currently work full-time in occupations imposing considerable cognitive demands (such as professor, manager, engineer, business owner, etc.). The remaining half was retired from the same type of occupations and had no current employment. Participants in the latter category were pre-screened by the UM Geriatrics Center and Institute of Gerontology to confirm eligibility in the study. Also, prior to the experiment, all participants were administered a cognitive impairment evaluation, as well as two divided attention assessments (for more details and the results of these examinations, see the cognitive assessment tools section below).

All participants reported normal to corrected-to-normal vision, no hearing impairments, and no compromised sense of touch. Table 3.1 summarizes the demographic background for each age group. All participants gave informed consent and were compensated for their time in the experiment at a rate of $20/hour and $40/hour, respectively, for younger and older adults, This difference in compensation was attributed to higher inconvenience costs incurred by older adult participants.

Table 3.1: Basic demographic factors for each age group

Factor	Younger adults	Older adults (working)	Older adults (retired)
Age	22.67 (SD = 2.71)	68.16 (3.76)	68.33 (2.20)
Years worked	–	34.06 (9.58)	34.86 (5.55)
Years retired	–	–	8.29 (4.55)
Male	8	6	5
Female	4	6	7
Games/puzzles (weekly)	7	4	2

The two older adult groups did not differ with respect to age and number of years worked. Research on aging suggests that numerous factors make the aging process heterogeneous in nature, such as occupation, mental stimulation, physical activity, and social engagement (Hawthorn, 2001; Oakley, 2009; Williams & Kemper, 2010). In particular, individuals with cognitively stimulating occupations, such as professors, physicians, and pilots, have been shown to maintain a higher level of cognitive functioning with age (Williams & Kemper, 2010). Therefore, our goal in recruiting participants from both working and retired older populations was to examine whether continued high cognitive demands affect perception and cognition. Older retired adults were asked to self-reported activities they frequently engage in in place of full-time employment (see Table 3.2). These regular activities consist mainly of physical exercise and volunteer work (such as distributing food at shelters, ushering at cultural programs, and assisting at local libraries and resale shops). Note that participants may appear in more than one category.

Table 3.2: Self-reported regular activities for older retired adult participants

Frequency	**Exercise**			**Volunteer work/ community service**
	Walk/jog/run	Gym workout	Yoga/Zumba	
~ 1hr/day	1	1		
2-4 hrs/day				2
1-2 times/week	1	3	2	3
3-5 times/week	5	1		2
Once per month				4

Cognitive assessment tools

All participants were administered three assessments to ensure that they were, in principle, able to perform the required tasks. The Montreal Cognitive Assessment (MoCA) detects early signs of mild cognitive impairment – the transitional state between normal aging and dementia. It examines 7 cognitive domains: visuospatial execution, naming, memory, attention, language, abstraction, and orientation (Nasreddine et al., 2005; Appendix 1B). A score of 26 or greater indicates normal or above normal performance. The remaining two assessments focused on participants' attentional capabilities. In the first one, a divided attention task developed by militantplatypus.com (a gaming database), participants were asked to track targets that moved around on a computer monitor in the presence of several visual distractors (see Figure 3.1). During each 20-second task, they were presented with a total of 16 spheres (blue and green spheres in the figure below) and asked to keep track of only the 1-3 blue ones. All 16 spheres moved randomly across the monitor. Eight seconds into the task, the blue targets turned green to match the distractors. After 12 seconds, all movement stopped, and participants were asked to indicate which of the 16 spheres had been presented in blue at the beginning of the task. The number of participants in each age group that could successfully track the required number of targets is listed in Table 3.3.

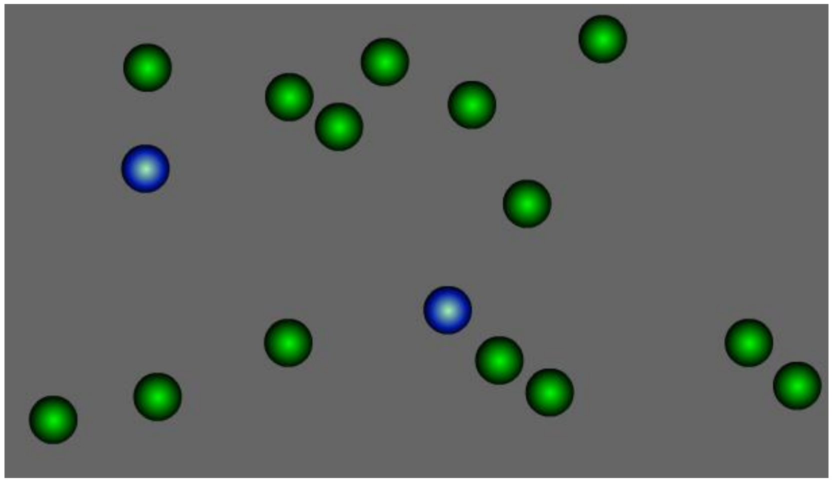


Figure 3.1: Divided attention task: tracking targets (blue) in the presence of other visual distractors (green)

The second divided attention assessment is part of the Cognitive Psychology Resource database developed by Xavier University of Louisiana (CAT Copyright 2003-2005, Bart Everson & Elliot Hammer, PhD: http://cat.xula.edu/thinker/perception/attention/divided). Here, participants were asked to perform two tasks in parallel: (1) follow a red target as it moved around the screen in a pattern that created a shape – without leaving an outline (left side), and (2) determine whether a series of words were spelled correctly by pressing the ‘yes’ or ‘no’ buttons (right side), Figure 3.2. One large shape and 6 possible words were presented during each 10-second task. The two tasks contributed evenly to the overall performance score. Specifically, fifty percent of the total 100% was awarded if the correct shape was named (0% otherwise). For the spelling task, if fewer than 6 words were recognized, the 50% for this task was weighted by the fraction of the number of words identified. Participants repeated this task 3 times, and their best score out of the three attempts was recorded. Table 3.3 summarizes the scores for each assessment for each group.

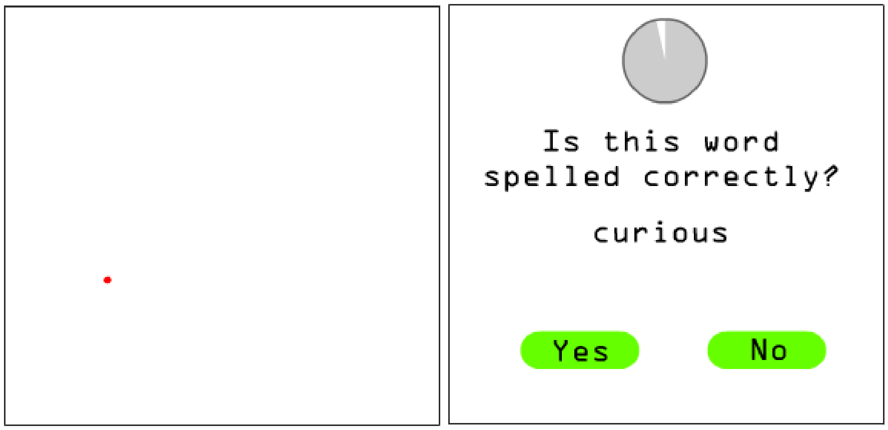


Figure 3.2: Divided attention task: shape recognition (left) and spelling tasks (right)

Table 3.3: Scores for cognitive assessments for each age group (1. average MoCA score; 2. tracking targets – total number of participants in group who could successfully track the required number of targets; 3. average weighted score for performing both tracking and spelling tasks)

Assessment	Younger adults	Older adults (working)	Older adults (retired)
MoCA (>26)	28.33 (SD = 1.07)	28.27 (1.49)	27.16 (1.34)
Tracking targets			
1/1 targets	12/12 (100%)	12/12 (100%)	12/12 (100%)
2/2 targets	10/12 (83.33%)	8/12 (66.67%)	7/12 (58.33%)
1/2 targets	2/12 (16.67%)	4/12 (33.33%)	5/12 (41.67%)
Shape/Spelling	75.69% (3.62%)	59.72% (5.01%)	41.0% (6.90%)

Multimodal experimental stimuli and apparatus

The stimuli and apparatus in this study are the same as those used in the crossmodal matching experiment in chapter 2. The visual stimulus was a blue light-emitting diode (LED). A standard-sized table tennis ball covered the light. The luminance range of the light was 0-126.77 cd/m^2. The light was located in the participant's peripheral vision, at an angle of approximately 35 degrees (10.5 inches) below the center of a 19" computer monitor on which participants were asked to fixate a centrally located X (Figure 3.3). Auditory cues were 350-Hz monotone beeps transmitted via stereo headphones, with a loudness range of 0-88 dB. Tactile cues were vibrations presented at 250 Hz (Jones & Sarter, 2008), using C-2 “tactors.” The tactile signal gain was on the range of 0-18 dB. Two adjacent tactors were attached to the back/middle of a Velcro belt fastened around participants’ waist, over clothing, and were in direct contact with the skin. These low frequency stimuli, for the light and sound, were selected to accommodate the age differences employed in this study. Pink noise was played over the stereo headphones to eliminate any audible sounds associated with the tactor vibrations. Overhead room lighting was turned off during this experiment.

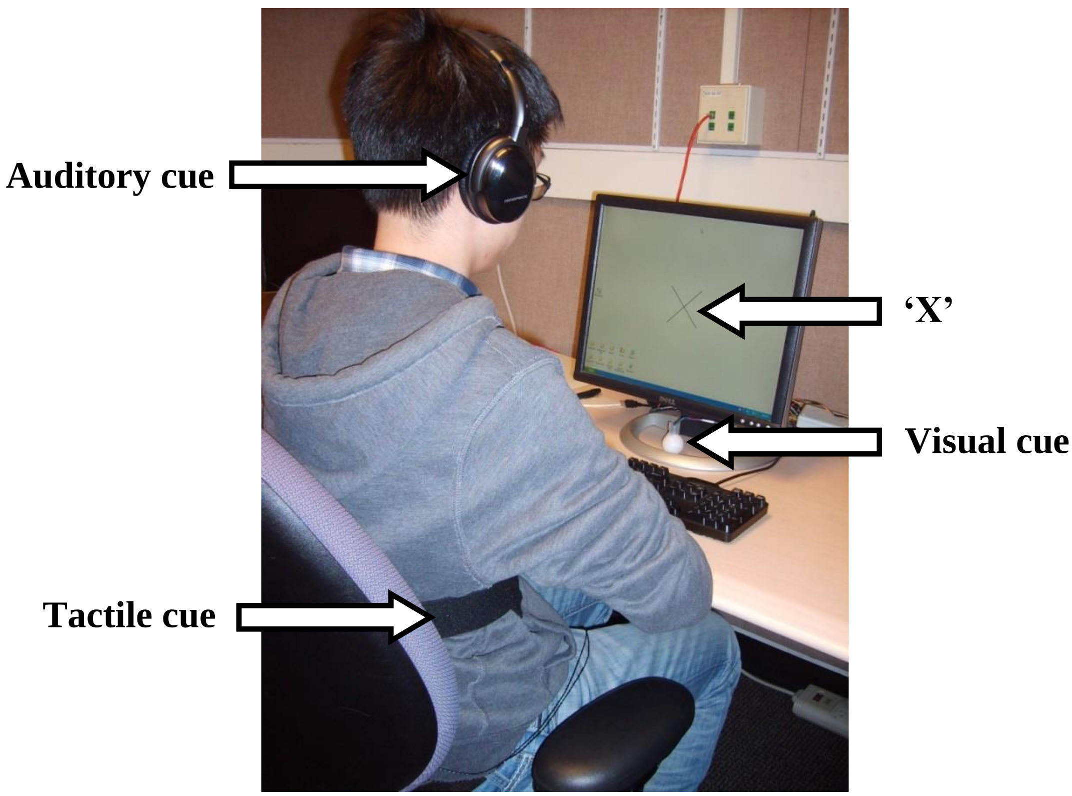


Figure 3.3: Experimental Setup

Crossmodal matching task

Crossmodal matching was performed to ensure that the visual, auditory and tactile experimental cues were equal in terms of perceived stimulus intensity (for more details about this procedure and its importance, see chapter 2). In particular, participants performed crossmodal matching using the keyboard technique that was shown to produce the least amount of within-subject variability in chapter 2 (Pitts, Riggs, & Sarter, 2015). Their task included the V-T, A-V, and T-A matching pairs, where the first cue represents the reference (fixed) stimulus and the second is the to-be-matched (variable) stimulus. Each reference cue stimulus was set at 50% of its total intensity and participants were asked to adjust the variable stimulus to find its equivalent. They repeated each match 5 times, for a total of 15 matches. The 5 values for each modality were then averaged to determine the final value for each participant. The values they selected for V, A, and T were presented to them both in insolation and in parallel multiple times to ensure that they were satisfied with their selections. Table 3.4 provides a summary of the final values selected by each age group.

Table 3.4: Crossmodal matching outcomes for each age group (1. match value – final value as a percentage of the total intensity spectrum selected by participants; 2. completion time – average time to match each modality pair; 3. reference cue replayed – average number of times participants replayed the reference cue; 4. variable cue direction changes – average number of times participants adjusted variable stimulus back and forth from increase to decrease or vice versa)

Match type	Factor	Younger adults	Older adults (working)	Older adults (retired)
A-V	Match value (%)	18.3%	15.6%	29.5%
	Completion time (secs)	14.31	15.1	17.2
	Reference cue replayed	2.2	2	2.75
	Variable cue direction change	2	1.5	1.5
T-A	Match value (%)	25.7%	9.8%	11.5%
	Completion time (secs)	11.5	15.2	21.1
	Reference cue replayed	2.7	2.1	3.2
	Variable cue direction change	1.4	1.2	1.5
V-T	Match value (%)	55.7%	61.3%	78.6%
	Completion time (secs)	31.7	34.0	39.2
	Reference cue replayed	4.3	3.4	4.5
	Variable cue direction change	2.0	1.5	1.6

Experimental design and procedure

The experiment employed a 3 (age group: younger, older working, and older retired) x 7 (cue/cue combination) full factorial design. The factor levels for cue combination were: visual (V), auditory (A), tactile (T), visual-auditory (VA), visual-tactile (VT), auditory-tactile (AT), and visual-auditory-tactile (VAT). Age was a between-subject variable, and cue combination was a within-subject variable.

After signing the consent form and being informed about the purpose of the experiment, participants were first asked to provide some biographical data (Appendix 1A). Specifically, they were asked about their daily activities, such as gaming habits, regular activities, and multitasking (see Tables 3.1 and 3.2 above for a summary of results). Next, each participant was administered the three cognitive assessments described above (Table 3.3). After completion of these steps, participants were introduced to the full range of multimodal stimuli they could use in the subsequent crossmodal matching task (see previous crossmodal matching section). The matching values they selected were used for the remainder of the experiment. Next, participants completed a training session to become familiar with their task and required responses. This training emulated the actual experiment, where participants were presented with a total of 49 cues (7 of each cue combination) that appeared every 6 seconds. They were asked to press the spacebar as quickly as possible and then verbalize the cue(s) detected in the order they were perceived. If, during training, participants realized that the stimuli were still not equivalent in terms of their salience, they were given the opportunity to repeat the crossmodal matching task. The training lasted approximately 4 minutes. In order to proceed to the next phase of the study, participants were required to reach a 90% accuracy level on the detection and response task.

For the experiment, participants were presented with 28 instances of each cue combination, which resulted in a total of 196 trials per person. Each participant was exposed to 49 cues in 4 separate blocks that lasted about 5 minutes each. In these blocks, cues/cue combinations were presented on average once every 6 seconds (range 4-10 seconds; the only difference from the training task), Figure 3.4. The order in which the cue combinations were presented was counterbalanced, and the duration of each cue event was 1 second. Throughout the experiment, participants were asked to fixate on the “X” located in the center of the screen to ensure that the light appeared in peripheral vision (Figure 3.3). As in the training, they were instructed to press the “spacebar” on the computer keyboard as soon as they “saw and/or heard and/or felt” a signal. They were asked to then verbally indicate the modality of cue(s) that they detected (using any phrasing of their choice, such as light, sound/tone, vibration/touch/buzz/back), in the order perceived. Participants were allowed to take short breaks in between blocks. Following the experiment, participants completed a debriefing session where they were asked to comment on their experiences, including any strategies they used, and provide feedback about the experiment. This full debriefing questionnaire can be seen in Appendix 1C. Altogether, the experiment lasted approximately 1 hour.

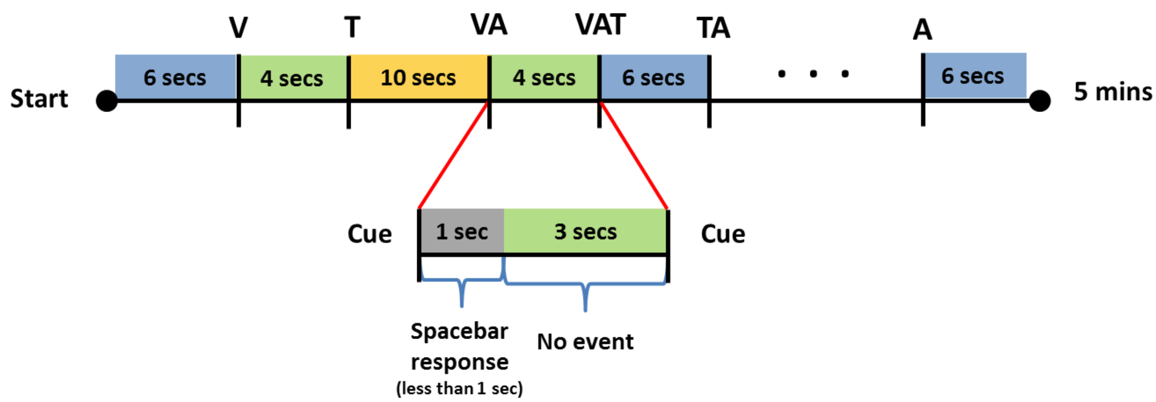


Figure 3.4: Sample 5-minute block of cue presentations with 1-second cue representation (49 total cue/cue combinations, i.e., 7 of each type; average 6 seconds between cues)

Dependent measures

The dependent measures were response time and accuracy of responses to each cue/cue combination. Response time (in milliseconds) was measured as the time between the onset of a cue/cue combination and the time at which the participant responded to that cue/cue combination, regardless of whether the response was correct or not. Accuracy (% correct) was a measure of the number of cue/cue combinations the participant correctly identified out of the total number of cue/cue combinations.

Signal detection theory (SDT) analysis was performed for each person and cue/cue combination. There were four possible responses to each cue presentation: (1) correct response (“hit”), (2) missed signal (“miss”), (3) substitution (“miss” and “false alarm”), or (4) false alarm (see Table 3.5). For example, if a person was presented with a visual-auditory (VA) stimulus pair and reported VA, then that was recorded as a correct response. However, if the participant reported only V or A or gave no response at all, that was classified as a missed signal. In case the person reported VT, we labeled this a substitution because tactile signal (T) was being substituted for A. Finally, a VAT response was considered a false alarm since T was not part of the original modality pair. Correct rejections were instances where the participant did not report any signal in addition to what was actually presented.

Table 3.5: Classification of possible responses to a visual-auditory stimulus combination

Cues presented	**Response**	**Classification**	**SDT measure**
VA	VA	Correct	Hit or correct rejection
VA	V or A or no response	Miss	Miss
VA	VT or TA	Substitute	Miss and false alarm
VA	VAT	Add	False alarm

The SDT analysis measures – sensitivity (d`; a measure of the ability to discriminate a signal from noise) and response bias (β; the likelihood of a person to identify a signal as a target) – were calculated. For response bias, a value greater than 1 is regarded as conservative (i.e., the observer is willing to declare a signal a target only in the presence of strong confirming evidence).

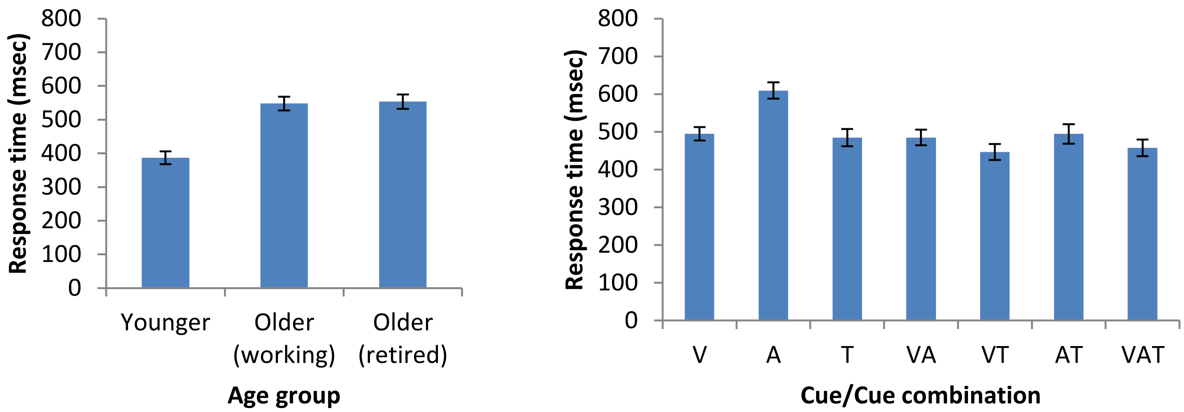
Results

A mixed-model repeated measures analysis of variance (ANOVA) was used to identify main and interaction effects. In addition, two-tailed Fisher's LSD post-hoc tests and paired comparisons were performed to determine differences between means for significant effects. Bonferroni corrections were applied for multiple statistical tests. Significance was set at $p < 0.05$ and partial eta squared (η_p^2) was used as a measure of effect size.

Signal detection analysis parameters – sensitivity (d`) and response bias (β) – involve calculations with the z-scores (from the normal distribution) of hit and false alarm rates. When hit or false alarm rates are 100% or 0% (which they often were in this study), they approach +/- infinity on the normal distribution curve. Therefore, a standard correction method was employed (Stanislaw & Todorov, 1999) that converted the minimum and maximum values of these rates to be 1/(2N) and 1 – (1/(2N)), respectively, where N is the number of trials over which each rate was calculated.

Response time

Overall, response time was significantly affected by age ($F(2, 33) = 10.142$, $p < 0.001$, $\eta_p^2 = 0.381$) and cue combination ($F(6,198) = 91.193$, $p < 0.001$, $\eta_p^2 = 0.734$). Response times for the younger adult group (mean = 387.20 msec, Mean Standard Error: MSE = 19.06) was significantly faster than for both older working adults (mean = 547.77, MSE = 20.67; $p = 0.002$) and older retired participants (mean = 553.40, MSE = 21.29; $p = 0.001$) adult groups, Figure 3.5(a). No significant difference was found between the two older adults groups ($p = 0.990$).



(a) (b)

Figure 3.5: Response times as a function of (a) age and (b) modality combination (errors bars represent mean standard error)

In general, response times to bi- and trimodal cue combinations were faster compared to single (unimodal) signals. Also, across all age groups, responses times to trimodal cues (mean RT = 457.73 msec, MSE = 18.07) were significantly faster than for bimodal cues (mean RT = 475.34, MSE = 18.41), followed by unimodal cues (mean RT = 529.69, MSE = 15.81; $p < 0.002$ in all cases). Table 3.6 shows the respective post-hoc comparisons for each cue presentations compared to one-another.

Table 3.6: Post-hoc comparisons for main effect of cue combination on response time (with associated response times – RT – and p-values)

Cue (RT in msec)	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**
V (494.90)							
A (609.33)	< 0.001						
T (484.83)		< 0.001					
VA (484.87)		< 0.001					
VT (446.42)	< 0.001	< 0.001	< 0.001	< 0.001			
AT (494.71)		< 0.001			0.001		
VAT (457.73)	0.002	< 0.001	< 0.001	0.002		0.001	

Figure 3.6 shows the response time comparison for each age group and cue combination, where both older adult groups responded 1.4 times slower than the younger group. No age group*cue combination interaction was observed.

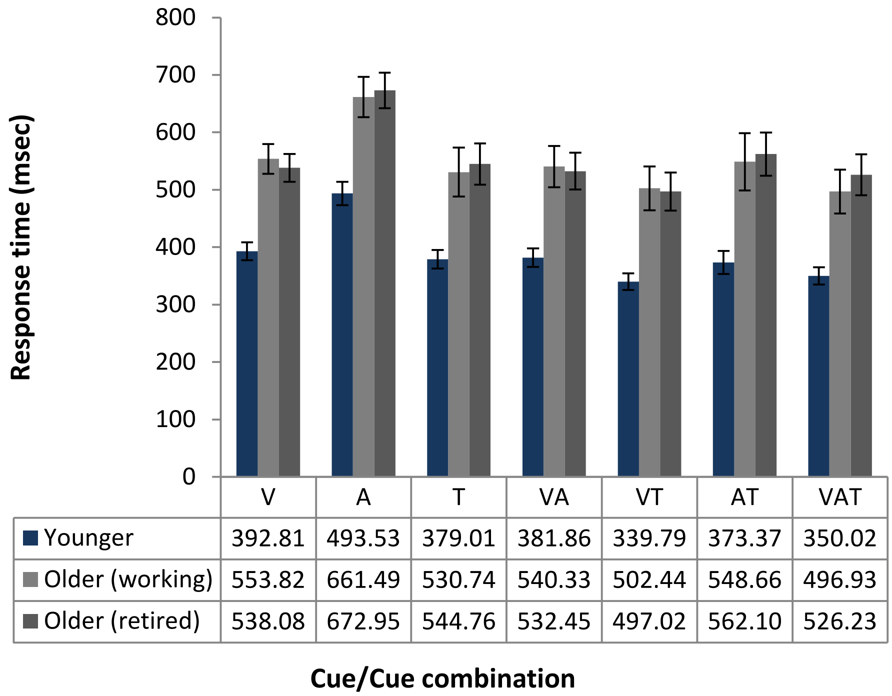
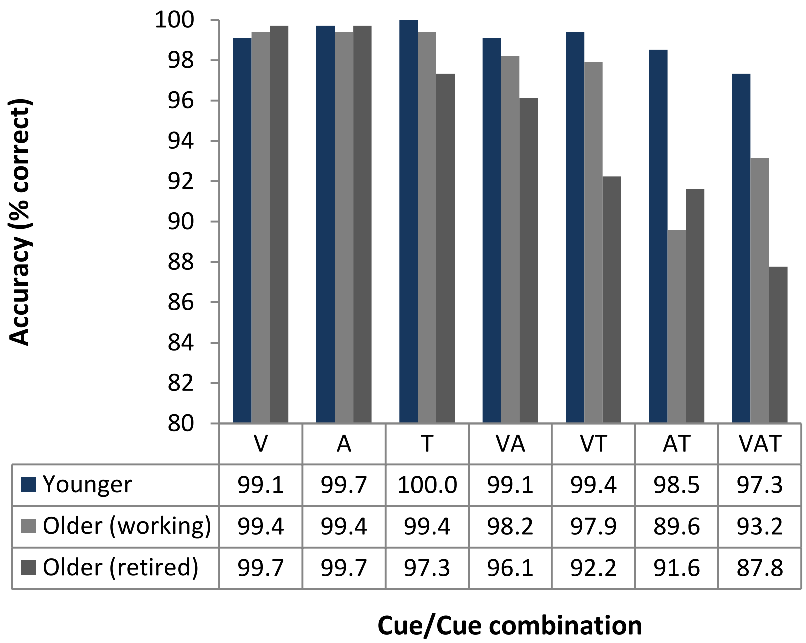


Figure 3.6: Response times as a function of age and modality/modality combination (errors bars represent mean standard error)

Accuracy

There was a significant main effect of age ($F(2, 33) = 4.090$, $p < 0.001$, $\eta_p^2 = 0.199$) and cue combination ($F(6, 198) = 12.258$, $p < 0.001$, $\eta_p^2 = 0.271$) on response accuracy. The older retired adult group provided a significantly higher percentage of incorrect responses compared to both the younger and older working adult groups. Specifically, retired individuals responded incorrectly to 5.1% of all cases (119 of 2,347 cues), as compared to 1% (23 of 2,351 cues) for younger adults and 3.3% (77 of 2,352 cues) for older working adults. A significant age group*cue combination interaction ($F(12, 198) = 2.127$, $p = 0.017$, $\eta_p^2 = 0.271$) was found also, such that, for older adults, accuracy significantly decreased as the number of signals increased. The signal detection analysis section below provides more detail about detection performance and response behavior for singles, pairs, and triplets of multimodal stimuli.



	V	A	T	VA	VT	AT	VAT
Younger	99.1	99.7	100.0	99.1	99.4	98.5	97.3
Older (working)	99.4	99.4	99.4	98.2	97.9	89.6	93.2
Older (retired)	99.7	99.7	97.3	96.1	92.2	91.6	87.8

Figure 3.7: Percentage of correct responses as a function of age and modality/modality combination

Tables 3.7–3.9 show the breakdown for all recorded responses for each group. Correct responses are shaded.

Table 3.7: Responses for younger adult group (23 incorrect responses of 2,351 cues)

Cues	Responses							
	V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	333							3
A	1	335						
T			336					
VA		1		332	2			
VT	1				334	1		
AT		4	1			331		
VAT				2	7		327	

For younger adult participants, the largest number of errors occurred for pairs (i.e., VA, VT, and AT) and triplets (i.e., VAT) of multimodal stimuli (10/23 and 9/23, respectively), Table 3.7. For VAT triplets, the most common error was not reporting the auditory cue (A). Very few substitutions (4/23) were observed.

Table 3.8: Responses for older (working) adult group (77 incorrect responses of 2,352 cues)

Cues	Responses							
	V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	334							2
A		334	1					1
T	1	1	334					
VA	5			330		1		
VT	5				329	1	1	
AT		11	1			301	22	1
VAT	1			13	7	2	313	

Table 3.9: Responses for older (retired) adult group (119 incorrect responses of 2,347 cues)

Cues	Responses							
	V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	334			1				3
A		335	1					
T			327			9		
VA	10	2		323			1	
VT	6		1		309	5	12	
AT		2	5		1	306	20	
VAT				28	11		294	

Similar to the younger group, individuals in both older adult groups gave more incorrect responses to doubles and triplets, compared to singles, Tables 3.8 and 3.9. In particular, older working individuals reported false information in 62% and 30% of cases for doubles and triplets, respectively. Likewise, older retired adults responded incorrectly to 56% (for pairs) and 34% (for triplets) of presentations across trials. In both age groups, the most common type of error for doubles was reporting a V when presented with the AT combination. For the VAT combination, on the other hand, more than half of the errors involved participants missing the T. Finally, substitutions again made up the smallest percentage of incorrect responses (6% and 5% for older working and older retired adults, respectively).

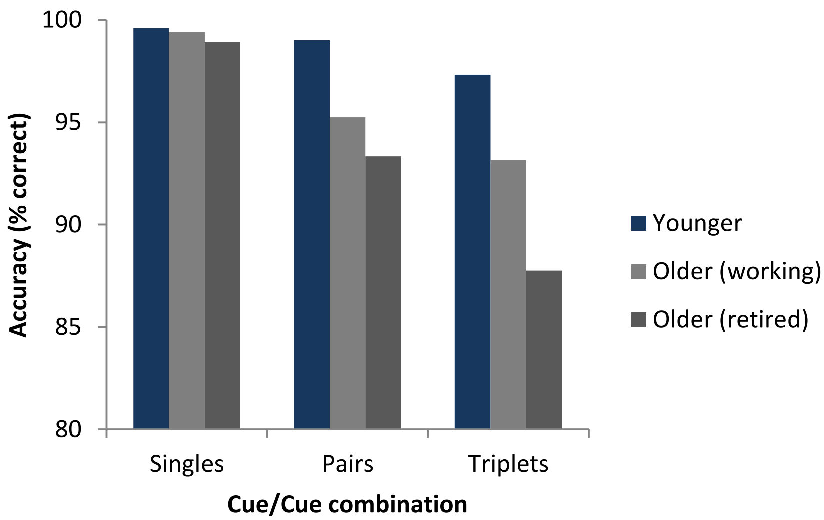


Figure 3.8: Percentage of correct responses as a function of age and modality combinations (singles, doubles, and triples of multimodal stimuli)

Signal detection analysis

Hite rate. As mentioned above, hit rate (accuracy) was significantly affected by both age and cue combination. Overall, hit rate for the **VAT** combination (hit rate = 92.8%; MSE = 1.7%) was significantly lower than for **V** (hit rate = 99.6%; 0.19%), **A** (hit rate = 99.8%; 0.11%), **T** (hit rate = 99.8%; 0.20%), and **VT** (hit rate = 98.3%; 0.64%; see Figure 3.9 for respective values). Similarly, hit rate for the **AT** pair (hit rate = 97.9%, MSE = 0.52%) was significantly lower than for **V**, **A**, and **T**. Post-hoc comparisons and associated p-values are listed in Table 3.10.

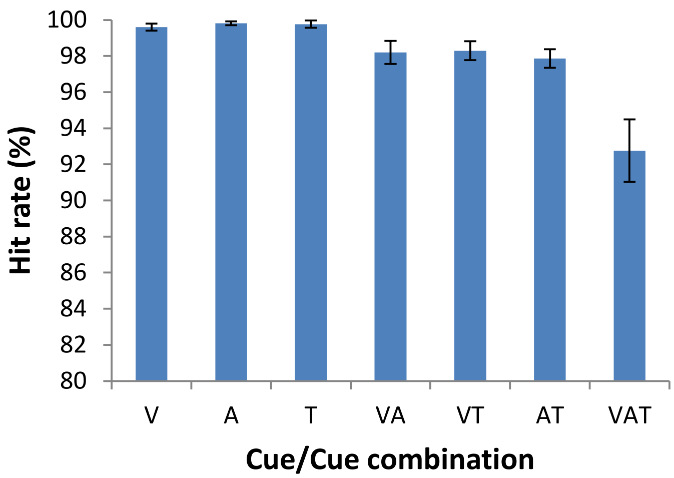


Figure 3.9: Overall hit rate as a function of modality combination (errors bars represent mean standard error)

Table 3.10: Post-hoc comparisons for main effect of cue combination on hit rate (with associated hit rates and p-values)

Cue (%)	V	A	T	VA	VT	AT	VAT
V (99.6%)							
A (99.8%)							
T (99.8%)							
VA (98.2%)							
VT (98.3%)		0.04					
AT (97.9%)	0.048	0.008	0.034				
VAT (92.8%)	0.005	0.003	0.002		0.052		

The above effects were more pronounced for older retired adults. For this group, hit rate for **VAT** (hit rate = 87.8%) was significantly lower compared to **V** (hit rate = 100%; p = 0.004), **A** (hit rate = 99.9%; p = 0.003), **T** (hit rate = 99.4%; p = 0.003), and **AT** (hit rate = 98.1%; p = 0.032). Also, accuracy for the **VT** (hit rate = 96.9%) condition was significantly lower than for **A** (p = 0.012) and **V** (p = 0.04).

Correct rejection. Correct rejections were not affected by age ($F(2, 33) = 2.501$, p = 0.097, $\eta_p^2 = 0.132$) nor cue combination ($F(12, 198) = 0.905$, p = 0.547, $\eta_p^2 = 0.158$), and there was no age group*cue combination interaction.

**Sensitivity (d`).** Sensitivity was significantly affected by age ($F(2, 33) = 4.740$, $p$ = 0.016, $\eta_p^2 = 0.223$) and cue combination ($F(6, 198) = 11.185$, $p < 0.001$, $\eta_p^2 = 0.253$). Younger adults (d` = 4.142; MSE = 0.062) were better able to distinguish between signal and noise, compared to older retired (d` = 3.876; 0.062) group only. There was no significant difference between the younger and older working groups. In general, all participants were better able to differentiate single stimuli, compared to doubles and triplets, Table 3.11.

Table 3.11: Post-hoc comparisons for main effect of cue combination on sensitivity (with associated d' values and p-values)

Cue (d`)	V	A	T	VA	VT	AT	VAT
V (4.159)							
A (4.238)							
T (4.173)							
VA (4.067)							
VT (3.989)		0.035	0.038				
AT (3.790)	0.002	0.001	0.002	0.023			
VAT (2.734)	0.001	< 0.001	< 0.001	0.026			

There was also a significant age group*cue combination interaction (F(12, 198) = 1.941, p = 0.032, η_p^2 = 0.105). Between groups, sensitivity was significantly different for the **AT** combination for the younger (d` = 4.176) and older retired (3.675; p = 0.030) participants. Within the older retired group, sensitivity was significantly lower for the:

- **VT** (d` = 3.675), **AT** (d` = 3.657), and **VAT** (d` = 3.536) cue combinations compared to both **V** (d` = 4.176) and **A** (d` = 4.200; $p < 0.05$ in all cases)

Within the older working group, sensitivity was significantly lower for the:

- **AT** pair (d` = 3.633) than for all other stimuli ($p < 0.05$) except **VAT**
- **VAT** triplet (d` = 3.676) compared to **V** (d` = 4.151; p = 0.76 – marginally different), **A** (d` = 4.245; $p$ = 0.004) and **T** (d` = 4.339; p = 0.011)

Response bias (β). In this study, there was a significant main effect of cue combination on response bias (F(6, 198) = 12.500, $p < 0.001$, η_p^2 = 0.275) and a significant age group*cue combination interaction (F(6, 198) = 2.381, p = 0.017, η_p^2 = 0.114). However, age alone did not significantly affect response bias. Overall, participants were more conservative in their responses to bi- and trimodal cues, compared to singles. In particular, in the **VAT** condition (β = 2.762, MSE = 0.377) participants needed much more evidence that all three stimuli were present before responding compared to all other cue combinations (mean β = 1.172, MSE = 0.942; $p < 0.05$ in all cases). This effect was more pronounced for the retired older adult group. Figure 3.10 below plot the sensitivity and response bias for the two older age groups only.

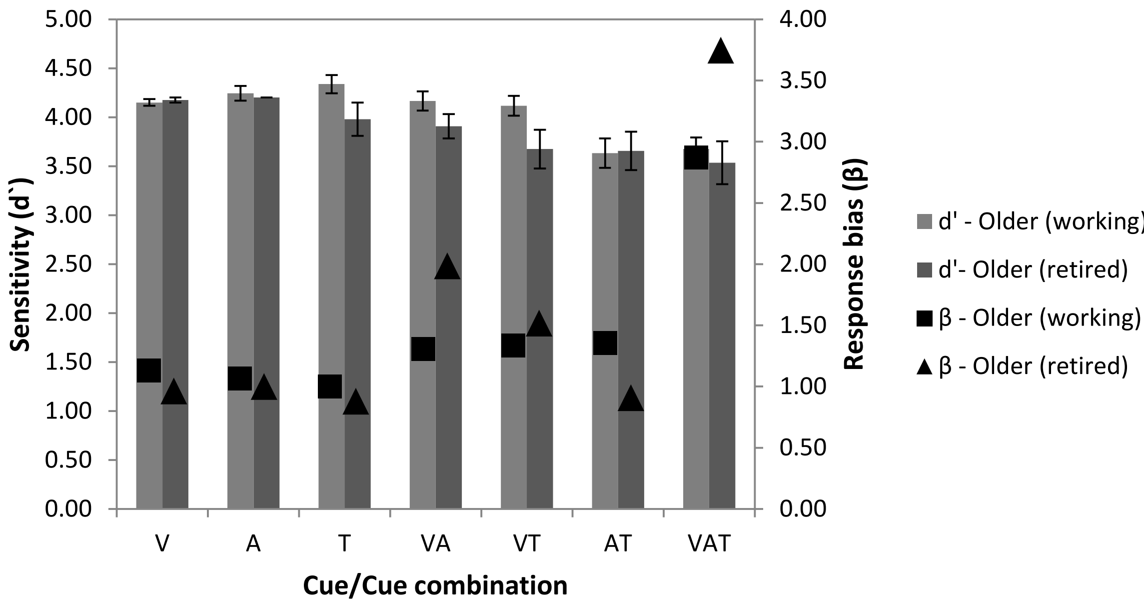


Figure 3.10: Sensitivity (d`; bars) and response bias (β, shapes) as a function of modality/modality combination for older working and retired adult groups (errors bars represent standard error)

Debrief questionnaire responses

A Friedman non-parametric test revealed that the subjective ratings of difficulty detecting cues were significantly affected by cue combination (χ^2(6, N = 36) = 86.036, $p < 0.001$). Ratings did not differ between age groups. Overall, participants rated trimodal **VAT** (4.35) and all bimodal pairs **VA/VT/AT** (mean for pairs = 3.19) more difficult to detect than **V** (1.76), **A** (1.67), and **T** (2.00) alone ($p < 0.005$ in all cases).

Discussion and Conclusion

Multimodal displays have been shown to support a number of cognitive functions, such as improved timesharing and interruption management. However, potential limitations of these designs are not well understood. Numerous studies have shown that people can process two concurrent signals in different sensory channels, such as visual and auditory, very effectively (e.g., Burke et al., 2006; Ho, Nikolic, & Sarter, 2001; Spence & Driver, 1997). However, only anecdotal and very limited empirical evidence exists on task performance studies when information is presented in vision, hearing, and touch at the same time. The goal of this study was to determine the extent to which people can process more than two unrelated signals in different sensory channels and to examine how aging affects this ability.

Overall, response time and accuracy were affected by both age and cue modality/modality combination. Performance for both older adult groups was significantly lower than for the younger group, but did not differ between the two groups. With respect to response time, older adults took 1.4 times as much time to respond to the same cue(s) as younger participants. Across all groups, response times decreased as the number of concurrent signals increased (specifically 529.7, 475.3 and 457.7 milliseconds for uni-, bi- and trimodal cues, respectively). In our study, response times to the auditory signals were longer compared to the other unimodal stimuli. Traditionally, this modality is responded faster than visual stimuli (e.g., Scott & Gray, 2008; Hecht, Reiner, & Karni, 2008a, 2008b). One possible explanation for this apparent discrepancy is that the pink noise that was played continuously over the stereo may have caused a slight processing delay as participants tried to distinguish the signal from the background noise.

The finding of faster response times to combined cues partially confirms the results reported by Laurienti, Burdette, Maldjian, & Wallace (2006) who showed that, for both younger and older participants, response times to combined visual-auditory cues (506 msec) were shorter than for either visual (576 msec) or auditory (669 msec) alone. One possible explanation for these differences is that the brain allocates greater attention to events that activate multiple sensory receptors at the same time (Hecht, Reiner, & Halevy, 2006; Diederich & Colonius, 2004). An alternative (and novel) explanation for these multisensory performance gains is that the response time to combined cues is dominated by the sensory stimulus with the fastest conduction velocity. In other words, the visual-tactile stimulus pair, for example, is responded to faster than the visual signal alone because participants first notice and immediately respond to the tactile signal.

In terms of accuracy, all three groups experienced more difficulty detecting signals in the case of combined cues, compared to single stimuli. This effect was much more pronounced in older (retired) adults who were more than 5 times as likely to miss one signal and more than 1.5 times as likely to miss more than one cue, compared to their older working and younger counterparts, respectively.

In the combined VAT condition – the modality combination not included in most earlier research –, older adults had an overall correct/hit rate of 90.5%. More than half of their errors in this condition involved the failure to report the tactile cue when it was presented concurrently with visual and auditory cues. In contrast, younger adults who had an overall hit rate of 97.3%, most often missed the sound (A) when it was combined with a visual and tactile stimulus. One possible explanation for these findings is that older individuals are less familiar with information presented via the sense of touch. In fact, individuals in these groups acknowledged that the tactile signal could be easily forgotten (quotes from the debriefing: "*I focused on tactile because sometimes I neglected it*" and "*Tried to focus on tactile so that I would not miss anything*"). The number of participants in this age group who attempted to employ this strategy is not known. Both in this experiment and in previous studies (e.g., Oskarsson, Eriksson, Carlander, 2012; Scott & Gray, 2008), participants responded faster to tactile stimulation, compared to visual and auditory cues, when it was presented in isolation. This effect was observed for both age groups. In other words, the tactile sensory modality appears to have the quickest conduction velocity and, as a result, should be noticed first. But in this particular case, it might have not been encoded into the sensory memory in time to avoid backwards interference from the other stimuli.

Our results partially support the findings of Hecht & Reiner (2009) who combined visual, auditory, and haptic (H; force) stimuli (requiring a separate response for each cue). In their study, participants also performed poorly in the VAH condition where they responded inaccurately to 6.8% of all trials (12,000 cues in total), compared to 7.2% in our study. However, only 2% of these errors were attributed to missing the H in the VAH condition. It is unclear whether these results are due to familiarity or salience of cues because there was no mention of crossmodal matching being performed which would ensure equivalence among stimulus intensities.

Another interesting finding is that, for AT pairs, approximately 25-30% percent of all errors made by the older working and retired groups involved a false alarm, specifically reporting a light (V) when none was present. This persistence effect, the sensation that a stimulus is still present even after it has ceased, has been observed in older adults (Hawthorn, 2000; McFarland, Warren, & Karis, 1958). One possible reason for this finding is that in the vast majority of cases (21/22 for older working and 18/20 for older retired participants), the preceding cue/cue combination included a visual stimulus (V, VT, VA and VAT). This may have led to a modality expectation for a visual stimulus (e.g., Langner, Kellermann, Boers, Sturm, Willmes, & Eickhoff, 2011; Spence, Nicholls & Driver, 2001). Also, the majority of these false reports were made when cues were presented within 6 seconds or less of each other. This combination of factors may have triggered an automatic response or recency effect (Broadbent & Broadbent, 1981; Hawthorn, 2000) in the visual modality, which is known to have a slower processing speed, compared to hearing and touch (e.g., Hecht, Reiner, & Karni, 2008a, 2008b; Lu et al., 2013). The significantly higher response times to cues found in elderly participants is likely the cause for this phenomenon being present in the older age group only. The additional time required to process this signal may have lead individuals to believe that it was still present even as the next signal appeared. Finally, during the experiment, participants were asked to focus their eyes on the ‘X’ in the center of the screen so that the light appeared in periphery view. The experimenter ensured that this instruction was followed. However, if at any time they did not focus on this target, it is possible that participants might have mistaken other elements as the visual stimuli.

In summary, our findings confirm that people are more likely to miss information if multiple unrelated signals are presented in parallel in different sensory channels. As expected, this effect was most pronounced for triplets and in older retired adults. Thus, this research represents an important first step towards identifying limits of multisensory information processing and presentation. However, one limitation of the present study is that participants could focus on the signal detection task which is not the case in most real-world environments. The next step in this line of research will therefore be to examine the detection of multiple multimodal cues in the context of an on-going task (driving, chapter 4). If similar results are found in the driving experiment, possible countermeasures to the above performance breakdowns will be developed and tested. They include offsetting one signal (specifically the tactile signal in the VAT condition) by just over 450 milliseconds (in either direction) to avoid signal interferences, such as crossmodal attentional blink (e.g., Martens & Johnson, 2005; Soto-Faraco et al., 2002) and masking effects, and thus increase the probability of the cue being detected. Also, false reporting of a signal may be avoided by slightly increasing the duration of signals to ensure that operators are better able to discriminate signal from noise.

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CHAPTER 4

Age-Related Differences in Detecting Concurrent Multimodal Cues while Multitasking: A Simulated Driving Study

The study presented in chapter 3 examined how well people can perceive and process non-redundant cues that appear at the same time in visual, auditory, and tactile form. It also investigated the extent to which aging modulates this ability. Older participants responded more slowly to all cue combinations and also made significantly more mistakes, especially for the combined bimodal auditory-tactile and trimodal visual-auditory-tactile cue combinations. In these cases, they often failed to report the tactile signal and also falsely reported a visual cue when none was present. One limitation of the study was that it did not require participants to perform an on-going task in parallel with detecting and reporting the various multimodal signals. It was thus not quite representative of the challenges faced by operators in data-rich, complex domains. Therefore, the experiment reported in this chapter examines the ability of older and younger adults to detect multimodal cues and cue combinations while performing a simulated driving task.

Driving was chosen as the application domain for this research because it imposes considerable attentional demands on operators. It is a complex pursuit tracking task that involves continuous visual scanning, manual control, and hand-eye coordination. Drivers are expected to engage in divided attention to notice and process the large amount of dynamic information being presented and updated continuously. For example, at any given time, a driver must be aware of vehicle speed and lane position, vehicles around him/her, curvature of the roadway, highway signs and signals, pedestrians, auditory signals from the environment such as public safety vehicle sirens and several other inputs. In recent years, driver assist systems have been introduced to automobiles to support drivers and increase safety. However, these technologies are often associated with their own displays and alarms/notifications and thus tend to further increase the information that needs to be considered by the vehicle's operator. For example, new in-vehicle systems provide personalized entertainment, navigation guidance, reversal assistance, blind spot notification, lane departure and collision warning. Some of these features, most notably collision warning, present information to previously underutilized sensory channels (in terms of information presentation), such as hearing and touch.

Driving was chosen as the application domain also because it is an activity that is being performed by a wide range of age groups, including the elderly. Over the next 30 years, the U.S. is projected to witness a more than 20% increase in adults aged 65 years and older (West et al., 2014). In 2008, the National Highway Transportation Safety Administration reported that older adults contributed to 15% of all traffic fatalities in the U.S. (NHTSA, 2008). This percentage is expected to increase to 25% by the year 2030. These high accident rates may be related, in part, to the findings of several driving studies that showed age-related deficits in sensory abilities, such as reduced visual acuity/peripheral field (e.g., Collins, Brown, & Bowman, 1989; Hawthorn, 2000; Schieber, 2003) and a decreased ability to detect higher frequency sounds (Hawthorn, 2000; He, Dubno, & Mills, 1998). Older adults have also been shown to experience difficulties with divided attention, including poor time sharing (e.g, Ponds, Brouwer, & van Wolffelaar, 1988; Somberg & Salthouse, 1982) and delayed response times to tasks (Laurienti, Burdette, Maldjian, & Wallace, 2006; Rabbitt, 1979). Individuals in this age group are also known to suffer from slower motor control movements (e.g., Smith, Sharit, & Czaja, 1999). These performance decrements put elderly patrons at a greater risk of being involved in a roadway collision. Ultimately, a major long-term objective of automobile manufacturers is to develop and deploy fully automated vehicles that can operate without human intervention, in part, because of the alarming nationwide accident statistics. However, in the interim, the automotive industry will continue to introduce new systems and associated interfaces in an attempt to make driving safer. As a result, driving may become more challenging for older adults as attentional demands across sensory channels are increased.

The goals of the present study are thus similar to those of the previous experiment (chapter 3): (1) establish whether people can reliably perceive and process non-redundant cues that appear concurrently in vision, audition and touch, and (2) investigate how aging modulates this ability. However, these questions are now examined in the context of a simulated driving task. Our hypotheses are the same as those in the generic detection experiment: we expect that performance (detection rate and response time) will suffer significantly if a person is asked to notice and report 3 (as compared to 2) simultaneous multimodal signals and that this performance decrement will be more pronounced in older participants. However, performance decrements are predicted to increase further in this study in the presence of the on-going visual/manual task for both younger and, even more so, older adults. Also, performance on the driving task is expected to suffer when participants are required to divide their attention between the driving and cue detection task.

Methods

Participants

The same 36 participants from the previous experiment (chapter 3) also volunteered to take part in this study: 12 younger adults (19-27 years), 12 older working adults (65-78 years), and 12 older retired adults (65-72 years). The second experiment took place approximately 6 months after the first and the requirements for participation were the same. However, in addition, all participants were required to have a valid U.S. driver's license. Prior to the experiment, all participants were again administered the two divided attention assessments to ensure that they could perform the required tasks (see Table 4.3 for results). Also, since the application domain for this study is driving, Table 4.1 displays additional demographic factors relating specifically to participants' driving experience and the features of their current vehicle. Please note for the assisted-driving technology, participants may appear in more than one category. Older adult participants were asked to report any perceptual and/or cognitive changes they noticed in themselves over the years (especially those related to driving), in addition to ways in which they overcome these obstacles, see Table 4.2. All participants gave informed consent and were compensated at a rate of $40/hour and $80/hour, respectively for younger and older adults. In addition, the top three performing participants in each age group received an additional 50% of their base pay as an incentive for outstanding performance on both the driving and signal detection tasks. The purpose of this bonus was to ensure that the participants assign the same priority to all tasks.

Table 4.1: Driving-related demographic factors for each age group

Factor	Younger adults	Older adults (working)	Older adults (retired)
Right hand dominance	12	12	12
# of years driving	6.54 (SD = 1.94)	50.13 (4.12)	50.67 (2.31)
Miles driven per week	43.75 (SD = 52.1)	103.67 (86.9)	96.67 (87.03)
Assisted-driving technology on current vehicle			
GPS Navigation	4	3	5
Back/side-view camera	3	6	6
Lane departure warning (visual and/or auditory)	1	–	1
Blindspot notification (visual and/or auditory)	3	2	2
Collision warning (auditory)	–	–	2
Traffic/weather update	3	1	1

Table 4.2: Most common self-reported perceptual and cognitive changes for both older adult participant groups

<table>
<tr><th>Domain</th><th>Issues</th><th>Implication for driving</th><th>Countermeasures</th></tr>
<tr><td rowspan="4">Perceptual</td><td rowspan="2">Reduced visual acuity (e.g., cloudiness and less focus)

(Reported in 17/24 participants)</td><td rowspan="2">• More difficult to drive at night
• Harder to drive in unclear weather
• Sensitivity to headlights
• Occasionally miss seeing road signs and other vehicles
• Difficulty judging distance of following vehicle</td><td>Technological:
• Change eyeglass prescription
• Use light filtering visor</td></tr>
<tr><td>Self-employed:
• Drive slower
• Double-check view
• Limit night driving
• Take breaks during longer drives
• Avoid looking at oncoming traffic and instead look towards the right side of the road
• Allow more vehicles to pass before changing lanes
• Take more time and look more frequently</td></tr>
<tr><td rowspan="2">Hearing changes (including minor hearing loss and tinnitus – ringing of ear)

(7/24 participants)</td><td rowspan="2"></td><td>Technological:
• Wear hearing aids</td></tr>
<tr><td>Self-employed:
• Increase volume</td></tr>
<tr><td rowspan="2">Cognitive</td><td>Attention (e.g., reduced ability to divide attention; shorter span)

(6/24 participants)</td><td>• Occasionally miss information about environment (such as signs and quickly moving vehicles)
• Cannot talk to others while driving</td><td>• Take frequent breaks
• Actively put more attention to driving
• Limit distractions (such as conversations, cellphones, etc.)</td></tr>
<tr><td>Memory (e.g., minor loss)

(6/24 participants)</td><td>• More difficult to recall events
• Loss of awareness when performing habitual tasks</td><td>• Make use of short notes and lists
• Practice memorizing
• Stop activity and think
• Self-assessment to correct behavior</td></tr>
</table>

Multimodal stimuli and apparatus

The stimuli and apparatus in this study are the same as those used in the crossmodal matching study (chapter 2) and the generic cue detection experiment (chapter 3). The visual stimulus was a blue LED light with luminance range: 0-126.77 cd/m^2. This light appeared in the participant's peripheral vision, at an angle of approximately 35 degrees (10.5 inches) below the center of a 30" computer monitor on which the driving task was presented (Figure 4.1). Auditory cues were 350-Hz monotone beeps transmitted via stereo headphones (loudness range: 0-88 dB). Tactile cues were vibrations presented at 250 Hz (Jones & Sarter, 2008), using C-2 "tactors," (signal gain range: 0-18 dB). Two adjacent tactors were attached to the back/middle of a Velcro belt fastened around participants' waist, over clothing, but in direct contact with the skin. These stimuli were selected to accommodate the age differences employed in this study. Pink noise was played over the stereo headphones to eliminate any audible sounds associated with the tactor vibrations. Overhead room lighting was turned off during this experiment.

Figure 4.1: Experimental setup (STISIM Drive simulation as background)

Driving Simulation

The experiment was conducted using a fixed-based medium-fidelity desktop driving simulation, STISIM Drive™ (Version 2) by Systems Technology, Inc., equipped with a Logitech force-feedback steering wheel and associated floor-mounted throttle and brake pedals. The simulation ran on a standard Windows-based computer and was displayed on a 30” monitor (see Figure. 4.1). The driving environment used in this experiment can be seen in Figure 4.2, where the view consisted of a standard roadway. No surrounding traffic, additional road scenery, sounds, or vibrations were present to avoid interference with the stimulus detection task required in this experiment.

Figure 4.2: Example driving environment in STISIM Drive™ simulation

The simulated highway consisted of straight sections and 30 moderate curves (e.g., total length of each curve ranged between 300-500 feet, including entry spiral length, curved section, and exit length). The suggested driving speed was between 45-50 mph throughout. Each curve could be negotiated without having to change the speed of the vehicle. The vertical curvature/elevation of the roadway was zero degrees throughout the experiment. A single lane of a two-lane highway (opposite directions) was used, which was 12 feet in width. In-vehicle displays included a standard analog speedometer and RPM gauge, a digital gear indicator, and an elevated rear-view mirror. The sampling rate of the driving-related parameters was 15 Hz.

Experimental design

As in the previous experiment, the study employed a 3 (age group: younger, older working, and older retired) x 7 (cue/cue combination) full factorial design. The factor levels for cue combination were: visual (V), auditory (A), tactile (T), visual-auditory (VA), visual-tactile (VT), auditory-tactile (AT), and visual-auditory-tactile (VAT). Age was a between-subject variable, and cue combination was a within-subject variable.

Experimental procedure

After signing the consent form and being informed about the purpose of the experiment, participants were first asked to complete a biographical data form (Appendix 1A) that, in this study, focused on their driving experience (see Tables 4.1 and 4.2 above for a summary). Next, each participant was administered the two divided attention assessments described in chapter 3 (tracking targets and shape recognition/spelling tasks, see Table 4.3 below for results).

Table 4.3: Scores for divided attention assessments for each age group (1. tracking targets – total number of participants in group who could successfully track the required number of targets; 2. average weighted score for performing both tracking and spelling tasks)

Assessment	Younger adults	Older adults (working)	Older adults (retired)
Tracking targets			
1/1 targets	12/12 (100%)	12/12 (100%)	12/12 (100%)
2/2 targets	10/12 (83.33%)	9/12 (75%)	7/12 (58.33%)
3/3 targets	6/12 (50%)	1/12 (8.33%)	2/12 (16.67%)
Shape/Spelling	88.13% (SD = 8.36%)	87.5% (22.0%)	75.69% (28.31%)

After completion, participants were introduced to the full range of multimodal stimuli they could use in the subsequent crossmodal matching task. Each person performed crossmodal matching using the same keyboard arrows method as in the generic detection task in chapter 3 (Pitts, Riggs, & Sarter, 2015). This was done to ensure that the visual, auditory and tactile cues were perceived as equal in terms of stimulus intensity. Participants performed a total of 15 matches that included the V-T, A-V, and T-A modality pairing (5 replications of each). The values they selected for V, A, and T were presented to them both in insolation and parallel multiple times to ensure that they were satisfied with these selections. The values they selected were used for the remainder of the experiment. Table 4.4 provides a summary of the final values selected by each age group.

Table 4.4: Crossmodal matching outcomes for each age group (1. match value – final value as a percentage of the total intensity spectrum selected by participants; 2. completion time – average time to match each modality pair; 3. reference cue replayed – number of times participants replayed the reference cue; 4. variable cue direction changes – number of times participants adjusted variable stimulus back and forth from increase to decrease or vice versa)

Match type	Factor	Younger adults	Older adults (working)	Older adults (retired)
A-V	Match value (%)	18.3%	17.4%	24.8%
	Completion time (secs)	11.67	12.14	19.18
	Reference cue replayed	2	1.6	1.87
	Variable cue direction change	1.89	1.22	1.13
T-A	Match value (%)	23.5%	7.8%	12.0%
	Completion time (secs)	12.57	12.41	25.42
	Reference cue replayed	2.55	1.69	2.8
	Variable cue direction change	1.41	1.22	1.27
V-T	Match value (%)	58.0%	65.5%	68.7%
	Completion time (secs)	15.59	20.53	29.21
	Reference cue replayed	3.45	1.69	3.28
	Variable cue direction change	1.81	1.22	1.43

Next, participants completed three separate training sessions to become familiar with the tasks and required responses.

1. *Detection task*: participants were presented with a total of 28 cues (4 of each cue combination) that appeared every 7 seconds. This reduction in cues, from 49 to 28 between the first and second experiments, was due to the fact that participants were familiar with the task after having completed experiment 1. They were asked to press a button on either side of the steering wheel (see Figure 4.3), as opposed to the ‘spacebar’ in the previous study) and then verbalize the cue(s) detected in the order perceived. Participants were instructed not to look directly at the visual cue. If, during training, participants realized that the visual, auditory, and tactile stimuli were still not equivalent

in terms of their perceived salience, they were given the opportunity to repeat the crossmodal matching task. In order to proceed to the next training phase, participants were required to achieve a 90% accuracy level on the detection and response task. The training lasted approximately 3 minutes.

2. *Driving task*: for the driving task, participants were first introduced to the simulated vehicle and associated controls and procedures. They were then asked to position themselves comfortably in front of the driving simulator, similar to the manner in which they drive normally. Next, they were instructed that their tasks were to maintain, as much as possible, a constant speed of 40 mph (58.67 ft/s) and also remain in the center of the lane (6 feet) at all times during the scenario. On a case-by-case basis, the experimenter determined whether participants needed to repeat the practice driving task. This was generally required in cases where participants failed to stay within 90% of the required speed and lane keeping performance during more than half of the practice trial. Before proceeding, participants were required to demonstrate that they could perform the task with an average speed and lane position within 5% of the requirements. The driving task lasted approximately 5 minutes.
3. *Driving and detection task:* this final part of the training session combined the two tasks. Participants were explicitly told that they should not prioritize one task over the other. This part of the training lasted approximately 5 minutes.

The experiment was nearly identical to the driving and detection task training. While driving the simulated vehicle and being asked to comply with lane keeping (6 meters) and speed requirements (40 mph), participants were presented with 28 instances of each cue combination. This resulted in a total of 196 trials per person. Each participant was exposed to 49 cues in 4 separate blocks that lasted about 5 minutes each. In these blocks, cues/cue combinations were presented on average once every 7 seconds (range 4-10 seconds; see Figure 3.4 in chapter 3 for an illustration of the 5-minute block of cue presentations). The duration of each cue event was 1 second. As during training, participants were instructed to press a designated button on either side of the steering wheel as soon as they “saw and/or heard and/or felt” (see Figure 4.3). They were asked to then verbally indicate the modality of cue(s) that they detected (using any phrasing of their choice, such as light, sound/tone, vibration/touch/buzz/back), in the order perceived. The order in which the cue combinations were presented was counterbalanced. Participants were allowed to take short breaks in between blocks. Following the experiment, participants completed a debriefing session where they were asked to comment on their experiences, including any strategies they used, and provide feedback about the experiment. The complete debriefing questionnaire can be seen in Appendix 1C. Altogether, the experiment lasted approximately 2 hours.

Figure 4.3: Logitech force-feedback steering wheel with associated response buttons (top red buttons on either side of the wheel) [Source: http://support.logitech.com/en_ca/product/momo-racing-force-feedback-wheel]

Dependent measures

The dependent measures for the detection task were again the response time and accuracy of responses to each cue/cue combination.

1. Response time – the time between the onset of a cue/cue combination and the time at which the participant responded to that cue/cue combination, regardless of whether the response was correct or not (in milliseconds)
2. Accuracy – the number of cue/cue combinations the participant correctly identified out of the total number of cue/cue combinations (% correct)

Signal detection theory (SDT) analysis was performed for each person and cue/cue combination. There were five possible responses to each stimulus presentation: (1) correct response ("hit"), (2) missed signal ("miss"), (3) substitution ("miss" and "false alarm"), (4) false alarm, or (5) correct rejection where the participant did not report any signal in addition to what was actually presented (refer to chapter 3 for an example case for each classification). The SDT analysis measures – sensitivity (d`; a measure of the ability to discriminate a signal from noise) and response bias (β; the willingness of a person to identify a signal as a target) – were calculated.

For the driving task, the following driving performance measures were calculated (and are most commonly used in the driving research, see Figure 4.4):

1. Longitudinal velocity (FV) – the forward speed of the subject vehicle (feet/second)
2. Lateral velocity (LV) – the horizontal component of speed of the vehicle, with respect to the center of the lane (feet/second; positive to the right)
3. Lateral lane position (LP) – a measure of the vehicle's displacement from the center of the lane, with respect to the roadway diving line (feet; 0-6 feet = right of center, 6-12 feet = left of center)

4. Steering wheel angle (SWA) – a measure of the steering wheel displacement from the initial resting position in a circular direction (degrees; positive to the right)

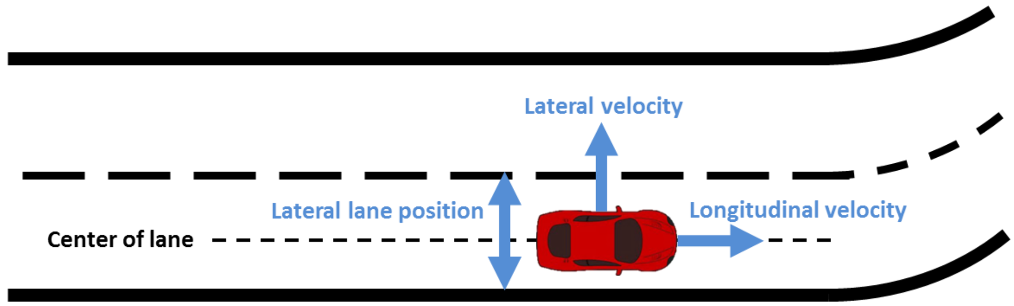


Figure 4.4: Illustration of driving performance measures

The goal in employing these metrics was to determine whether the processing of challenging cue combinations (in particular, triplets) affected driving performance. For each of the above measures, absolute deviations (magnitude of deviation in either direction) were calculated. For example, for lateral lane position, absolute deviations indicated how far away the vehicle was from the 6-feet target in the center of the lane. The mean (average) for each driving measure was calculated for both 3 seconds before and 3 seconds after the initiation of cue/cue combination (see Figure 4.5). Then, the difference between 'after' and 'before' was recorded. Since the shortest amount of time between cues was 4 seconds (in very few cases), 3 seconds was the minimum amount of time that could be used to avoid interference from the previous or subsequent event. No cue was presented while participants were driving inside of curves neither at a distance near a curve that would infer with driving performance. Also, the stimulation scenarios were designed such that participants could remain at a constant speed of 40 mph while in the moderate curves.

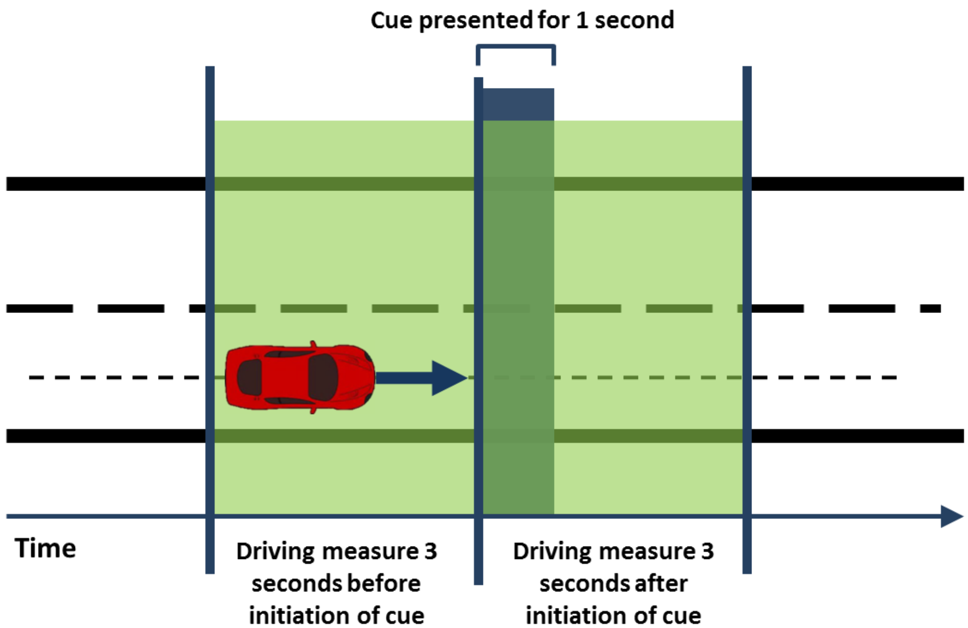


Figure 4.5: Illustration of 3 seconds before and 3 seconds after initiation of the 1-second cue presentation used for data analysis

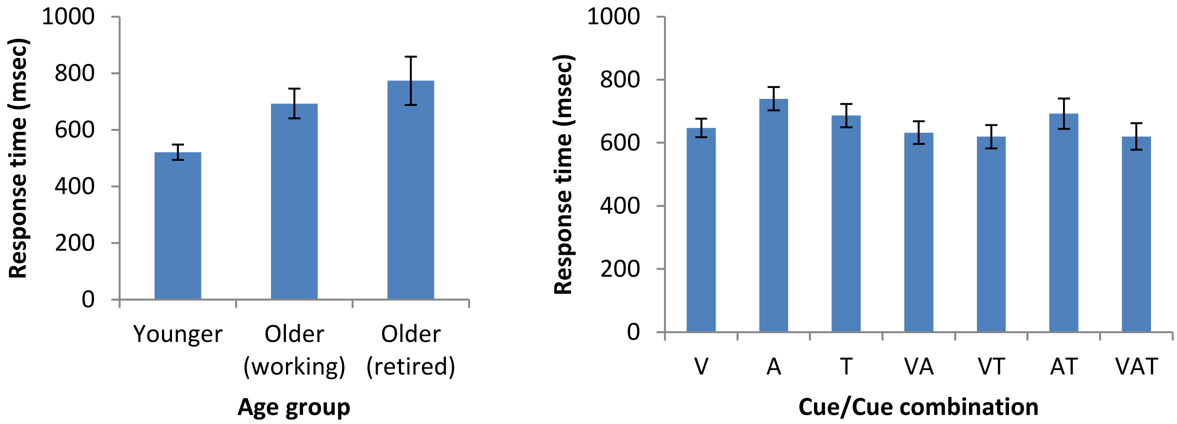
Results

A mixed-model repeated measures analysis of variance (ANOVA) was conducted to identify main and interaction effects. In addition, two-tailed Fisher's LSD post-hoc tests and paired comparisons were performed to determine differences between means for significant effects. Bonferroni corrections were applied for multiple statistical tests. Significance was set at $p < 0.05$ and partial eta squared (η_p^2) was used as a measure of effect size. Similar to the experiment in chapters 3, a standard correction method (Stanislaw & Todorov, 1999) was used to calculate sensitivity (d`) and response bias (β) for signal detection analysis.

Response time

There was no significant difference in response time between accurate and inaccurate responses. Therefore, the following analysis combines both types of responses.

Response time was significantly affected by age ($F(2, 33) = 4.982$, $p = 0.013$, $\eta_p^2 = 0.232$) and cue combination ($F(6, 198) = 15.742$, $p < 0.001$, $\eta_p^2 = 0.323$). The average response time for the younger adult group (mean = 520.89 msec, MSE = 27.03) was significantly faster than for the older retired group (mean = 773.24, MSE = 52.47; $p = 0.012$), but not compared to the older working group (mean = 692.75, MSE = 85.19; $p = 0.129$), Figure 4.6. There was no difference between the two older adults groups ($p = 0.995$) and no age group*cue combination interaction was found.



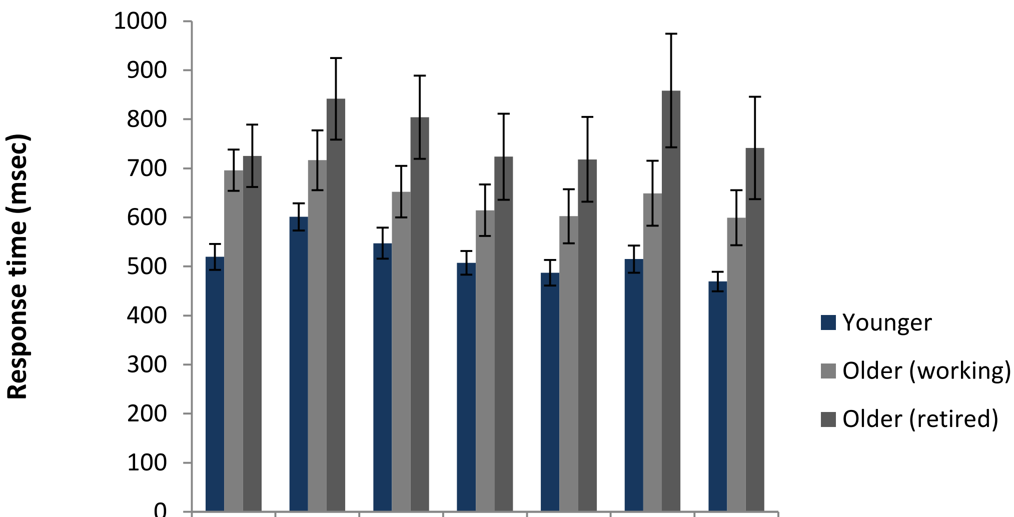
(a) (b)

Figure 4.6: Overall response times as a function of (a) age group and (b) modality/modality combination (errors bars represent mean standard error)

Table 4.5: Post-hoc comparisons for main effect of cue combination on response time (with associated response times – RT – and p-values)

Cue (RT in msec)	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**
V (646.90)							
A (739.59)	< 0.001						
T (686.02)		0.018					
VA (632.20)		< 0.001					
VT (619.21)		< 0.001	0.007				
AT (692.11)		0.034			0.003		
VAT (620.04)		< 0.001				0.013	

Figure 4.7, below, shows the response times comparison for each age group and cue combination, where both older adult groups responded 1.48 times slower than the younger group.



	V	A	T	VA	VT	AT	VAT
Younger	519.45	601.03	547.32	507.40	486.87	514.85	469.31
Older (working)	695.84	716.42	652.37	614.44	602.39	648.99	599.31
Older (retired)	725.39	841.60	804.01	723.54	718.16	858.41	741.55

Cue/Cue combination

Figure 4.7: Response times as a function of age and modality/modality combination (errors bars represent mean standard error)

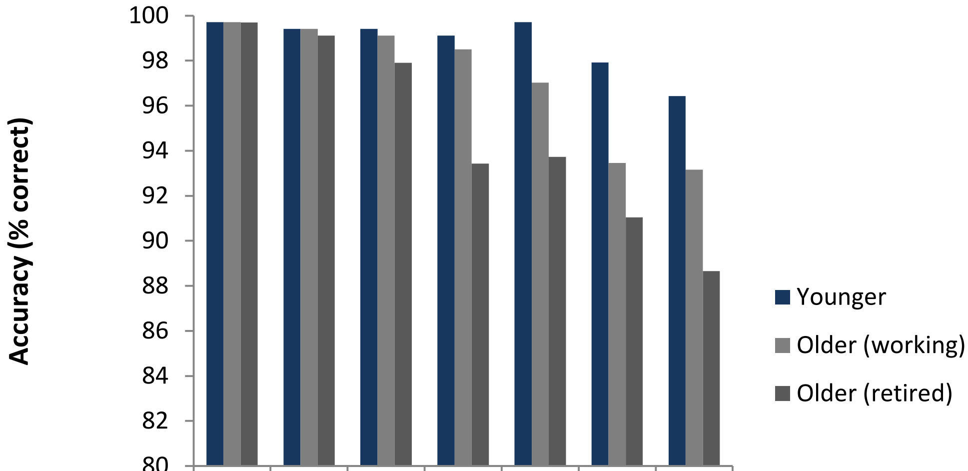
Also, across all age groups, responses times to trimodal cues (mean RT = 620.04 msec, MSE = 38.34) were significantly faster than for bimodal cues (mean RT = 647.84, MSE = 36.14), followed by unimodal cues (mean RT = 690.83, MSE = 30.195; $p < 0.03$ in all cases).

Accuracy

There was a significant main effect of cue combination ($F(6, 198) = 12.258$, $p = 0.001$, $\eta_p^2 = 0.107$) and a marginally significant effect of age ($F(2, 33) = 2.794$, $p = 0.076$, $\eta_p^2 = 0.145$) on hit rate. No age group*cue combination interaction was found.

Specifically, the hit rate was significantly lower for **VAT** (hit rate = 92.8%, MSE = 1.6%) than for **V** (hit rate = 99.7%, MSE = 0.2%, $p = 0.002$), **T** (hit rate = 99.2%, MSE = 0.4%, $p = 0.007$), and **VT** (hit rate = 97.4%, MSE = 0.8%, $p = 0.30$). This was true also for **AT** (hit rate = 96.7%, MSE = 0.7%) compared to **V** ($p = 0.007$) and **T** ($p = 0.011$), see Figure 4.8.

Also, the older retired adult group had a higher percentage of incorrect responses compared to both the younger and older working adult groups. In particular, retired individuals responded incorrectly to 5.2% of all cases (122 of 2,346 cues), as compared to 1.2% (28 of 2,352 cues) for younger adults and 2.8% (66 of 2,351 cues) for older working adults.



	V	A	T	VA	VT	AT	VAT
Younger	99.7	99.4	99.4	99.1	99.7	97.9	96.4
Older (working)	99.7	99.4	99.1	98.5	97.0	93.5	93.2
Older (retired)	99.7	99.1	97.9	93.4	93.7	91.0	88.7

Cue/Cue combination

Figure 4.8: Percentage of correct (hit rate) responses as a function of age and modality/modality combination

Correct rejection. Correct rejections were not affected by age (F(2, 33) = 0.949, p = 0.398, η_p^2 = 0.054) nor by cue combination (F(6, 198) = 1.214, p = 0.275, $\eta_p^2 = 0.069$), and there was no age group*cue combination interaction.

Sensitivity. Sensitivity (d`) was significantly affected by age ($F$(2, 33) = 3.707, $p$ = 0.035, $\eta_p^2$ = 0.183) and cue combination ($F$(6, 198) = 9.915, $p$ < 0.001, $\eta_p^2$ = 0.231). However, no age group*cue combination interaction was found. Younger adults (d` = 4.1; MSE = 0.073) were better able to distinguish between signal and noise, compared to both older working (d` = 3.971; MSE = 0.073) and older retired (d` = 3.819; MSE = 0.073) groups across all trials. For cue combinations, all participants were better able to differentiate single stimuli, compared to doubles and triplets (see Table 4.6 for post hoc comparisons between the multimodal stimuli).

Table 4.6: Post-hoc comparisons for main effect of cue combination on response time (with associated response times – RT – and p-values)

Cue (d`)	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**
V (4.176)							
A (4.051)							
T (4.097)							
VA (4.004)							
VT (4.002)	0.026						
AT (3.755)	0.001		0.008	0.027			
VAT (3.658)	< 0.001	0.003	< 0.001	0.009	0.002		

Response bias. In this study, there was a significant main effect of cue combination (F(6, 198) = 12.850, p < 0.001, η_p^2 = 0.280) and age (F(2, 33) = 4.210, p = 0.024, η_p^2 = 0.203) on response bias. However, there was no significant age group*cue combination interaction. Overall, participants were more conservative in their responses to triplets and doubles, compared to singles. In the **VAT** condition, compared to all other cue combinations (p < 0.05 in all cases), participants needed much more evidence that all three stimuli were present before responding, Figure 4.9). Older retired adults displayed a significantly higher response bias (β = 1.993, MSE = 0.199), compared to the younger (β = 1.230, MSE = 0.199, p = 0.032) participants. There was no significant difference between the two older adult groups.

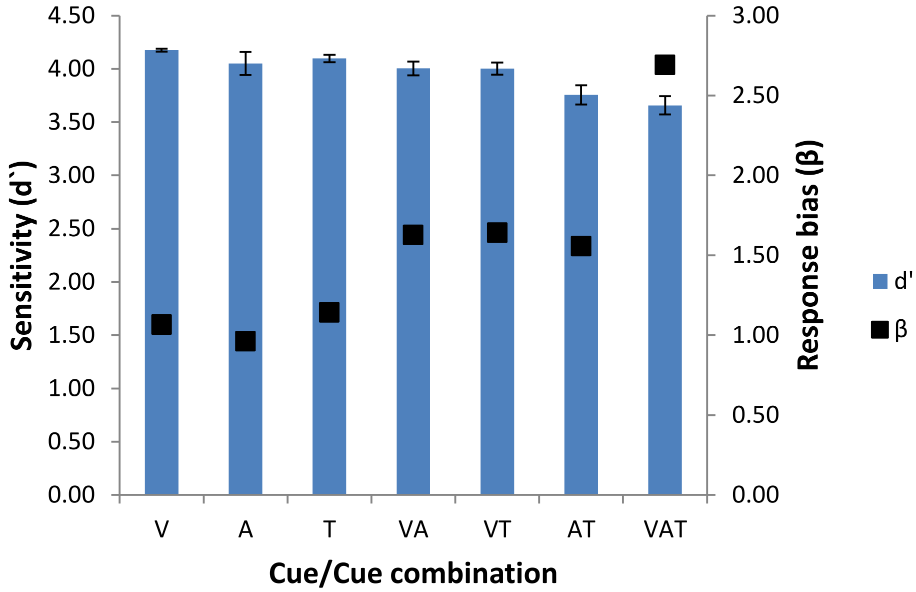


Figure 4.9: Sensitivity (d`; blue bars) and response bias (β, black squares) as a function of cue modality combination for all participants (errors bars represent standard error)

Tables 4.7- 4.9 show the breakdown for all recorded responses for each group. Correct responses are shaded.

Table 4.7: Responses for younger adult group (28 incorrect responses of 2,352 cues)

		Responses							
		V	A	T	VA	VT	AT	VAT	None
Cues	V	335							1
	A	2	334						
	T			334			1		1
	VA	1			333	1	1		
	VT					335		1	
	AT		4	3			329		
	VAT				3	8	1	324	

For younger adult participants, the largest number of errors occurred for pairs (i.e., VA, VT, and AT) and triplets (i.e., VAT) of multimodal stimuli (39% and 43%, respectively). For pairs, participants gave more false responses to signals involving AT (no bias towards modality combination). However for triplets, the most common error committed was omitting the auditory cue (A), when it was combined with vision (V) and touch (T) – in few cases. Substitution accounted for 14% of all errors.

Table 4.8: Responses for older (working) adult group (66 incorrect responses of 2,351 cues)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	335							1
	A	1	334				1		
	T		1	333			1		1
	VA	3	1		330			1	
	VT	5		4		326		1	
	AT		12		1		314	9	
	VAT	1			18	4		313	

Similar to the younger group, older working individuals gave more incorrect responses to doubles and triples, compared to singles, Table 4.8. This group reported false information in 56% and 35% of cases for doubles and triples, respectively. The most common type of error was observed for the AT combination (in 57% of errors involving pairs). In this condition, participants most often did not report the A when it was combined with T (55% of AT misses). Also, 41% of AT misses involved false reports of a V in combination, even though none was present. For the VAT combination, on the other hand, more than 75% of the errors occurred when participants omitted the T. Substitutions contributed to the smallest percentage of incorrect responses (4.5%).

Table 4.9: Responses for older (retired) adult group (122 incorrect responses of 2,346 cues)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	334							1
	A		333				3		
	T			328			1		6
	VA	19	2		313	1			
	VT	18				314	1	1	1
	AT		10	1	1		305	16	2
	VAT	1			26	10	1	297	

The older retired group also gave more incorrect responses for doubles and triples, Table 4.9. Individuals in this category provided inaccurate responses to 60% (for pairs) and 31% (for triplets) of presentations across trials. For pairs, 90% and 86% of errors for VA and VT, respectively involved participants responding only with V. For AT, 53% of errors consisted of falsely reporting V even though none was present. Finally, for the VAT combination, participants did not report the T when it was presented with V and A in 68% of cases.

Debrief questionnaire responses

A Friedman non-parametric test revealed that the subjective ratings of difficulty detecting cues were significantly affected by cue combination (χ^2(6, N = 36) = 60.694, $p < 0.001$). Ratings did not differ between age groups. During the driving task, participants rated trimodal **VAT** (4.44), and bimodal **VT** (3.83) and **AT** (4.08), significantly more difficult to detect compared to **V** (2.64), **A** (1.92), **T** (2.69), and **VA** (3.00) ($p < 0.01$ in all cases).

Table 4.10: Summary of significant main and interaction effects, and post-hoc comparisons for response time and accuracy for age and modality combination (RT – response time; Signal detection parameters: P(H) – hit rate; P(CR) – correct rejection; d` - sensitivity; β – response bias)

Metric	Age	Cue combination	Interaction
RT	**Younger < older working & retired** **---** $F(2, 33) = 4.982$, $p = 0.013$	**A > all combinations; T > VT; AT > VT & VAT** **---** $F(6, 198) = 15.742$, $p < 0.001$	Not significant
P(H)	**Older retired < younger and older working** --- $F(2, 33) = 2.794$, $p = 0.076$	**VAT < V, T & VT; AT < V & T** **---** $F(6, 198) = 12.258$, $p = 0.001$	Not significant
P(CR)	Not significant	Not significant	Not significant
d`	**Younger > older working & retired** **---** $F(2, 33) = 3.707$, $p = 0.035$	**VAT < all combinations; AT < V, T, VA; VT < V** **---** $F(6, 198) = 9.915$, $p < 0.001$	Not significant
β	**Older retired > younger** **---** $F(2, 33) = 4.210$, $p = 0.024$	**VAT > all combinations** **---** $F(6, 198) = 12.850$, $p < 0.001$	Not significant

Driving performance

As mentioned earlier, participants were asked to maintain a constant speed of 40 mph (58.67 ft/s) and to keep the vehicle as close as possible to the center of the lane (lateral lane position of 6 feet). The following table summarizes the average forward velocity and lateral lane position for each age group over the total driving period during instances when no cue was present. No significant difference was found for these metrics between the groups.

Table 4.11: Average speed and lane position during driving simulation when no cue was present for each age group

Age group	Speed (ft/s)	Lateral lane position (ft.)
Younger	54.63 (SD = 1.41)	6.11 (0.28)
Older (working) adult	55.03 (2.68)	6.11 (0.46)
Older (retired) adult	55.98 (2.96)	6.16 (0.33)

The sections below present, for each driving measure, the difference in average values for 3 seconds before and 3 seconds after the initiation of each cue presentation. For the calculation of magnitude (absolute) deviations, the absolute value of this difference was used.

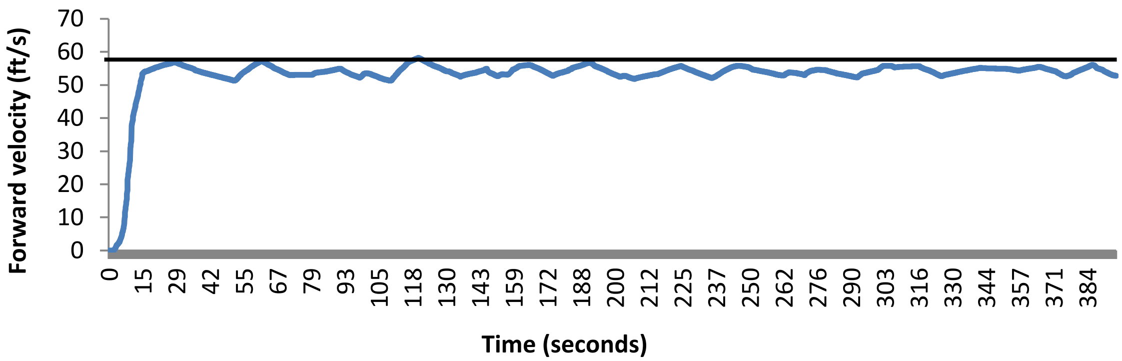


Figure 4.10: Sample forward velocity plot recorded over one of four 5-minute experimental trials while being presented with cues (black horizontal line represents 58.67 ft/s speed requirement)

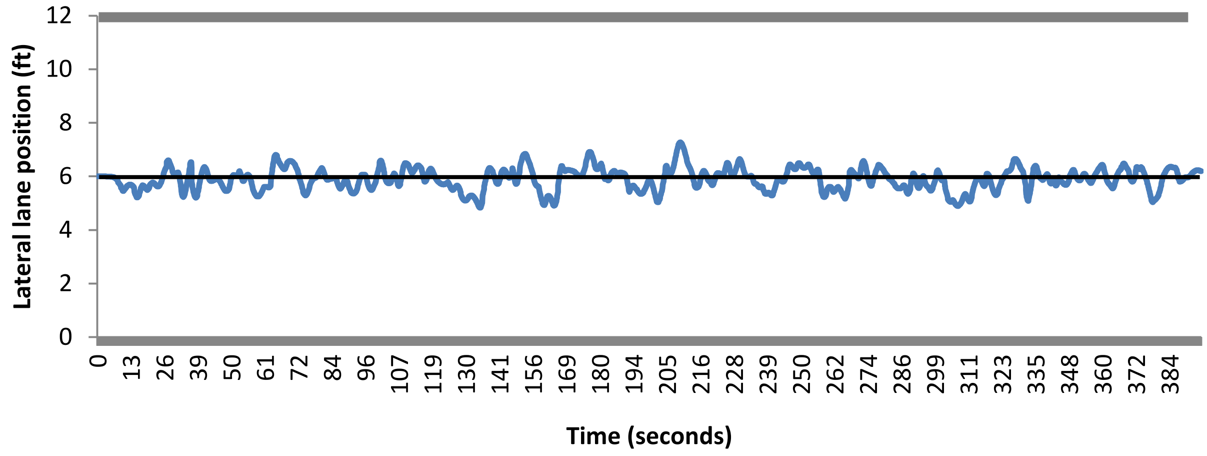


Figure 4.11: Sample lateral lane position plot recorded over one of four 5-minute experimental trials while being presented with cues (bold gray horizontal lines represent right – 0 feet – and left – 12 feet – lane boundaries; thin black horizontal line represents 6 feet lane position requirement)

Forward (longitudinal) velocity. The average deviation in forward velocity was significantly affected by cue combination ($F(6, 198) = 8.026$, $p < 0.001$, $\eta_p^2 = 0.196$), but not by age ($F(2, 33) = 2.51$, $p = 0.097$, $\eta_p^2 = 0.293$), see Figure 4.12. There was no age group*cue combination interaction. Participants changed their speed the most after being presented with **VAT** (by 1.07 ft/s, MSE = 0.41) compared to **V** (0.919 ft/s, MSE = 0.41, $p = 0.002$), **A** (0.849 ft/s, MSE = 0.44, $p < 0.001$), **T** (0.9 ft/s, MSE = 0.05, $p = 0.007$), and **VA** (0.78 ft/s, MSE = 0.46, $p < 0.001$). Also, speed deviations for **VT** (0.99 ft/s, MSE = 0.42) were significantly higher than for **A** (0.849 ft/s, MSE = 0.42, $p < 0.001$) and **VA** ($p < 0.001$).

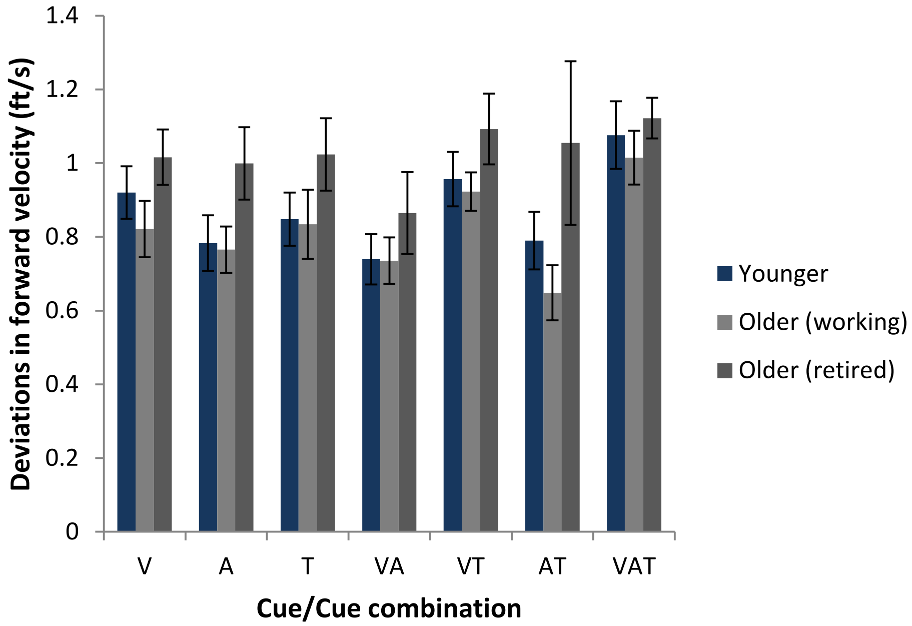


Figure 4.12: Average absolute deviations in forward velocity for each age group (errors bars represent standard error)

Lateral velocity. The magnitude of changes in lateral velocity was affected by age (F(2, 33) = 5.975, p = 0.006, η_p^2 = 0.266), but not by cue combination (F(6, 198) = 1.549, p = 0.358, η_p^2 = 0.045), see Figure 4.13. There was also no age group*cue combination interaction. Changes in lateral velocity were significantly higher for the two older adult groups (0.347 ft/s and 0.330 ft/s, respectively for the older retired and working participants) compared to the younger population (0.234 ft/s; $p < 0.05$ in both cases). However, changes in lateral velocity did not differ between the two older adult groups.

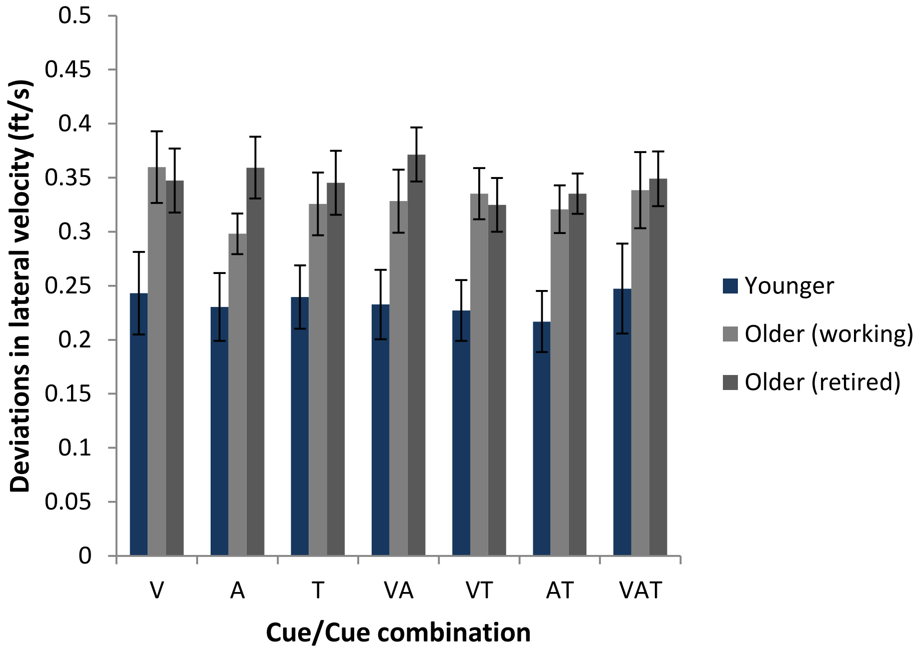


Figure 4.13: Average absolute deviations in lateral velocity for each age group (errors bars represent standard error)

Lateral lane position. Similar to lateral velocity, deviations in lane position 3 seconds after the initiation of a cue were significantly affected by age ($F(2, 33) = 11.432$, $p < 0.001$, $\eta_p^2 = 0.429$). There was no main effect of cue combination ($F(6, 198) = 0.394$, $p = 0.882$, $\eta_p^2 = 0.012$). Deviations (in either direction) in lateral lane position were significantly higher for the two older adult groups (0.661 ft. and 0.618 ft., respectively for the older retired and working participants) compared to the younger group (0.383 ft.; $p < 0.003$ in both cases, see Figure 4.14). However, lane position deviations did not differ between the two older adult groups.

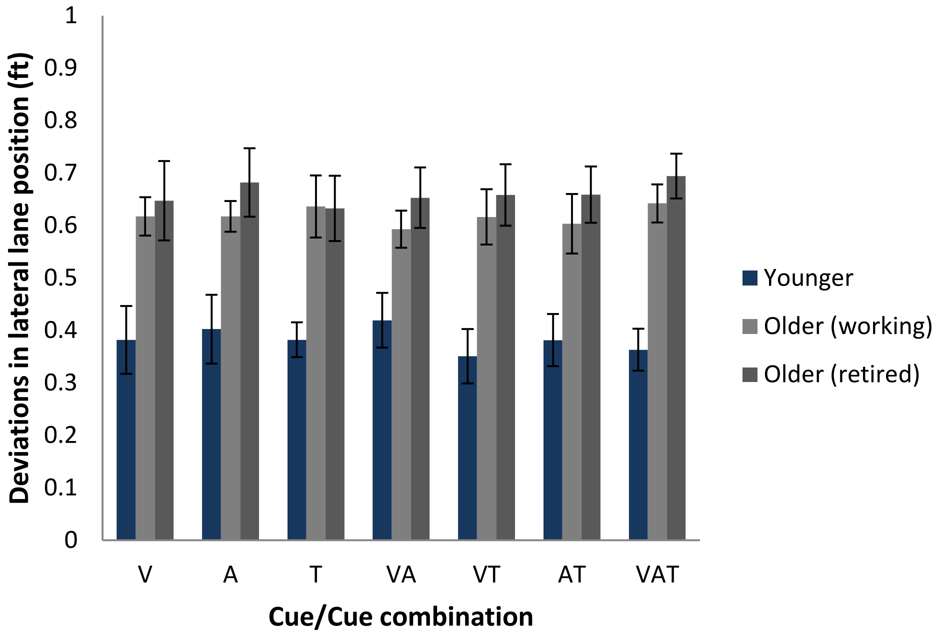


Figure 4.14: Average absolute deviations in lateral lane position for each age group (errors bars represent standard error)

Steering wheel angle. The magnitude of changes in steering wheel angle were significantly affected by cue combination ($F(6, 198) = 73.911$, $p < 0.001$, $\eta_p^2 = 0.691$). However, there was no main effect of age on changes in steering wheel angle ($F(2, 33) = 0.740$, $p = 0.485$, $\eta_p^2 = 0.043$) and no age group*cue combination interaction. The largest average angle observed during the driving task was 6.918° (MSE = 0.150°) when participants were presented with combined **VA** (see Figure 4.15). This was significantly larger than all other cue combinations ($p < 0.01$ in all cases). Similarly, the steering angle after the tactile stimulus was presented (angle = 6.672°, MSE = 0.150°) also larger than all other combinations, except **AT** (angle = 6.579, MSE = 0.127°).

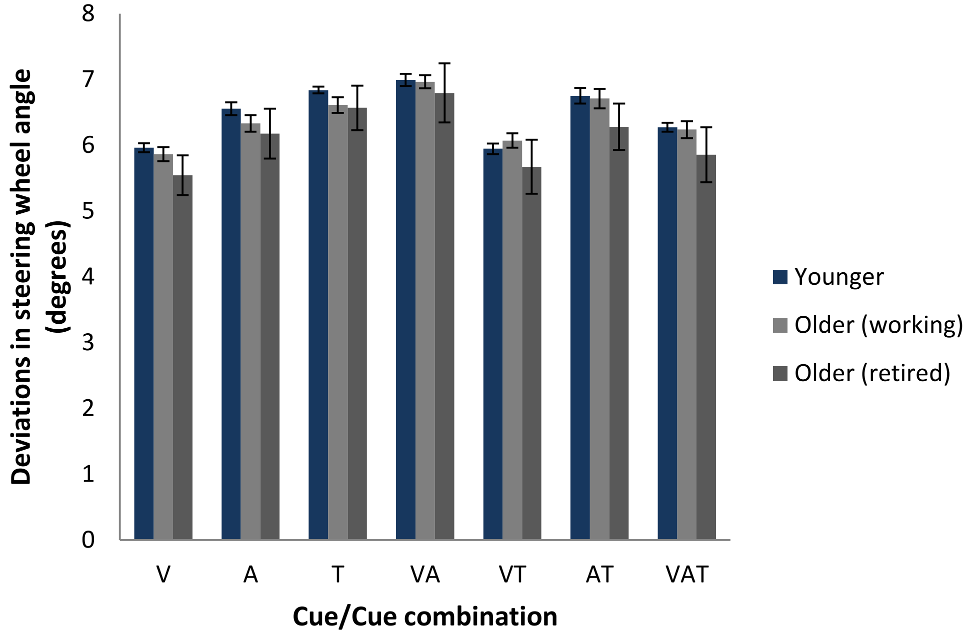


Figure 4.15: Average absolute deviations in steering wheel angle for each age group (errors bars represent standard error)

Table 4.12: Summary of significant main and interaction effects, and post-hoc comparisons for driving performance metrics calculated by the difference between 3 seconds after and 3 seconds before the initiation of each cue presentation (average difference in absolute values)

Metric	Age	Cue combination	Interaction
Forward velocity	Not significant	**VAT > V, A, T, VA; VT > A & VA; VA > V** **---** $F(6, 198) = 8.026, p < 0.001$	Not significant
Lateral velocity	**Older working and retired > younger** **---** $F(2, 33) = 5.975, p = 0.006$	Not significant	Not significant
Lateral lane position	**Older working and retired > younger** **---** $F(2, 33) = 11.432, p < 0.001$	Not significant	Not significant
Steering wheel angle	Not significant	**VA > all combinations;** **T > all combinations except AT** **---** $F(6, 198) = 73.911, p < 0.001$	Not significant

Discussion and Conclusion

Similar to the experiment reported in chapter 3, this study examined how reliably younger and older adults can perceive and process non-redundant cues in vision, audition, and touch when these cues appear individually or in pairs and triplets. However, this question was now examined in the context of a simulated driving task to assess the effects of competing attentional demands on multimodal information processing. In that sense, the experiment was more representative of the many real-world environments for which multimodal displays are being developed.

Response time and accuracy

As expected, response time was affected by age and cue modality/cue combination. On average, the two older adult groups responded 1.5 times slower than the younger participants to all cues/cue combinations. Similar time differences have been reported in previous research that investigated age-related differences in information processing speeds of combined cues (e.g., Laurienti, Burdette, Maldjian, & Wallace, 2006; Rabbitt, 1979). Across all age groups, response times to triplets (620 msec) were faster than for pairs (648 msec) which, in turn, were responded to faster than single cues (691 msec). These performance gains are one of the reasons why researchers have employed redundant cue combinations in the past (Hecht, Reiner, & Karni, 2008a, 2008b; Miller, 1982; Van Erp & Van Veen, 2004). Note that, even though the signals employed in the current study were not redundant, the observed benefits were the same. This suggests a generalized effect where presenting participants with two or more inputs at the same time increases vigilance/alertness and attention to signals (Bertelson and Tisseyre 1969; Hecht, Reiner, & Karni, 2008b; Posner, Klein, Summers, & Buggie, 1973; Sanders 1980). As mentioned in chapter 3, response times to combined cues may also have been faster because they were dominated by the sensory modality with the fastest conduction velocity/stimulation rate.

Age and cue combination also affected accuracy. Older retired adults provided more incorrect responses to all bi- and tri-modal modality combinations than the other groups, and accuracy declined for all participants when they were presented with more than one cue at a time. In particular, 78% and 68% of (a total of 23 and 38) errors for older working and older retired adults, respectively, involved the failure to report a tactile cue (T) when it was presented in combination with both a visual (V) and an auditory (A) cue. One possible reason for this finding is crossmodal spatial links in attention (e.g., Ferris & Sarter, 2008; Spence & Driver, 1997). When information in one modality is presented to a particular body location or in a particular direction, this leads to an increased readiness to perceive information in a different modality in the same location or direction (Spence & Driver, 1997a). In this study, visual cues and the driving task were presented on/below the monitor in front of the participants. However, vibrations were applied to their back. This may have increased the likelihood of tactile cues being missed. The tactile cue might have been noticed and reported more often if stimuli had been presented to areas of the body with lower perceptual thresholds, and thus higher sensitivity, such as the fingers, hands, or face (Sherrick & Cholewiak, 1986). An additional reason why older participants may have missed a considerable number of tactile cues is their very limited exposure to signals in this modality. Younger participants, in contrast, are more frequently exposed to touch technology in everyday life, such as video games or cellular phones. For this group, only 12 errors occurred when they were presented with triplets. This speaks to their overall better ability to divide attention among multiple channels and signals. Of the errors in this group, 66% involved omission of the A, rather than T.

For stimulus pairs involving V (both VA and VT), 86% of errors in the older retired participant group consisted of reporting only the V. Similarly, Hecht & Reiner (2009) found that 88% and 78% of errors for VA and VH(aptic), respectively, involved reporting the V only. These findings may be explained by visual dominance (Colavita, 1974), the tendency of a person to report only the visual component of a bimodal visual-auditory or visual-tactile stimulus, a well-documented phenomenon in studies that employ bimodal (Sinnett, Spence, & Soto-Faraco, 2007; Ward, 1994) and trimodal cues (Hecht & Reiner, 2009). Another possible reason for these observations is modality priming, a top-down influence on attention. Since the driving task was primarily visual, 9/12 individuals in both older groups explained that they focused their attention mainly on the visual scenery to ensure they were correctly performing the driving task. This may have led them to expect, and be more prepared for, signals in the visual channel (Buchner, Zabal, & Mayr, 2003; Driver & Baylis, 1993; Spence & Driver, 1997b; Spence, Ranson, & Driver, 2000).

An unexpected finding for AT pairs in both older groups was that 41% and 53% of all errors for older working and retired adults, respectively, involved falsely reporting a V. In the 93% these cases, the preceding cue/cue combination included a visual stimulus (V, VT, VA and VAT), which may have led to a modality expectation for a visual stimulus (e.g., Langner et al., 2011; Spence, Nicholls & Driver, 2001). Nearly all of the false reports were made when the timing between two cues was 7 seconds or less. This suggests a persistence effect (Hawthorn, 2000; McFarland, Warren, & Karis, 1958), where the sensation of a previously presented visual stimulus is still present.

Driving performance

For the driving task, all three groups stayed within 5-7% of the required the speed limit (40 mph; 58.67ft/s) and lane position (6 feet from right- and left-side lane boundaries) when no cue was present. However, as expected, performance suffered once participants were presented with a multimodal signal and now asked to provide both a manual and verbal response. In particular, deviations in lateral lane position and lateral velocity were most affected by age, while forward velocity and steering wheel angle were affected by cue combination.

Lane position and lateral velocity. Deviations (in either direction) from the original lane position, 3 seconds prior to the cue presentation, were significantly greater for the two older adult groups (mean deviation = 0.64 ft.), compared to the younger group (0.38 ft.). An identical trend was observed for lateral velocity, which is essentially calculated as the change in lateral lane position over time. These findings did not depend on any specific cue combination. This can be explained by the fact that older individuals, in addition to displaying longer response times to cues, also engaged in mental processing for a longer period of time after each cue presentation. This was necessary for them to determine the correct assignment of each signal they were presented with before verbally responding. In turn, the additional processing time interfered with their monitoring and adjusting of lane position. Also, older adults exhibit slower motor control (e.g., Larsson, Grimby, & Karlsson, 1979; Ross, Rice, Vandervoort, 1997; Smith, Sharit, & Czaja, 1999), which could have resulted in delayed correction (recovery) times after they had been presented with a cue/cue combination. These findings partially confirm those in previous work which found that, compared to younger participants, older adults were 17% less accurate in maintaining proper lateral lane when being presented a choice-reaction time task in parallel (Ponds, Brouwer, & van Wolffelaar, 1988).

Another possible explanation is the interference between the two manual inputs required to perform the tasks. The driving task required turning the steering wheel, while the detection task required pressing the response button. With respect to Multiple Resource Theory (MRT), the act of responding to each signal (spatial tactile response) may have interfered with the on-going processing of the spatial visual/manual driving task (Wickens, 1980, 1984, 2002, 2008; Wckens & Hollands, 2000). These performance decrements may have not been present if instead only verbal responses were required (van Wolffelaar, Rotthengatter, & Brouwer, 1991).

Forward Velocity. In terms of forward velocity (speed), participants most often either sped up or slowed down after being presented with the VAT combination (more so than for the other cues/cue combinations). One explanation for this finding is that a trimodal cue presentation requires a higher level of mental processing and thus interferes more with speed maintenance. Presenting information to all three sensory modalities at the same time, while engaged in a driving task, may simply exceed the resources supplied/available (Wickens, 2008; Wickens & Hollands, 2000). In this particular case, task performance suffered as a result of an upper processing limit in attentional resources. Coupled with a higher processing requirement, the novelty of T is suggested to have influenced speed changes. Modality combinations, VT and T – both of which contain a tactile signal – resulted in the second and third greatest deviations in forward speed, respectively.

Dual-task performance in older adults. Overall, our findings imply that the older population experienced more difficulties with divided attention (Craik & Salthouse, 2011; McDowd & Craik, 1988; McDowd, Vercruyssen, & Birren, 1991). However, the results did not necessarily confirm previous studies that suggest that, when older adults are presented with a dual-task paradigm, they perform well on one and either mediocre on or even drop the second altogether (e.g., Broadbent & Heron, 1962). Rather, in addition to poorer performance on the detection task (i.e., slower response times and higher error rates), both older adult groups struggled more with the driving task after being presented with various cue combinations than did their younger counterparts. In other words, older participants did not perform comparatively well on either task. Similar to previous work, our instructions and the incentive used in these experiments encouraged participants to assign equal priority to all tasks. However, participants may have failed to adopt this strategy or did not develop an effective timesharing strategy.

In conclusion, similar to chapter 3, findings from the current study suggest that people are likely to miss signals when more than two unrelated sources of information are presented at the same time. This effect was more pronounced in retired older adults. Surprisingly, these participants more often reported owning a vehicle that employs multisensory assisted-driving technology, such as visual/auditory lane departure and auditory collision warning systems, compared to the other groups. However, they also indicated that they did not have much of a desire, and indeed did not use these systems much.

While detection performance in this experiment was overall rather good (the lowest detection rate was approximately 88%), missing even just one signal in the context of a real-life situation could result in a near-miss or an accident. The same is true for delayed responses to various cues and cue combinations. Thus, the experiment identified operationally significant limits of multimodal information processing. The subsequent chapter, chapter 5, will provide a comprehensive comparison between the two experiments reported in chapter 3 and 4 which differed by a single factor, task condition: single- (generic) and dual- (driving) task.

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CHAPTER 5

Comparison of Age-Related Differences in Detecting Concurrent Multimodal Cues in Single- and Dual-Task Conditions

The study presented in chapter 3 examined how well younger and older adults can reliably perceive and process non-redundant cues that appear simultaneously in vision, hearing, and touch without interference from an on-going task. Chapter 4, on the other hand, investigated this same question, but in the context a simulated driving task. They both highlighted important potential limitations of multimodal information processing and presentation, such as omissions and false reports of combined signal components. To this end, the purpose of this chapter is to provide a comparison between the two experiments which differed by a single factor, task condition: single- (generic) and dual- (driving) task.

Methods

The same 36 participants volunteered to take part in both studies and were divided into three groups: younger, older working, and older retired. A collection of demographic factors for each of these groups can be found in chapters 3 and 4. In both studies, all participants were administered two divided attention assessments (tracking targets and shape recognition/spelling tasks). Table 5.1, below, shows a side-by-side comparison of the scores, for each age group, between the two experiments.

Table 5.1: Comparison of divided attention assessments scores between the single- and dual-task experiments for each age group (1. tracking targets – total number of participants in group who could successfully track the required number of targets; 2. average weighted score for performing both tracking and spelling tasks)

Assessment	**Younger adults**		**Older adults (working)**		**Older adults (retired)**	
Tracking targets	Single-task	Dual-task	Single-task	Dual- task	Single-task	Dual-task
1/1 targets	12/12	12/12	12/12	12/12	12/12	12/12
2/2 targets	10/12	10/12	8/12	9/12	7/12	7/12
Shape/Spelling	75.69 (SD = 3.62)	88.13% (8.36)	59.72 (5.01)	87.5% (22.0)	41.0 (6.9)	75.69% (28.31)

In addition, in both studies, each participant performed an identical crossmodal matching procedure on the multimodal stimuli (Pitts, Riggs, & Sarter, 2015). Table 5.2 provides a summary of measures collected for each group between the two experiments.

Table 5.2: Comparison of crossmodal matching outcomes between the single- and dual-task experiments for each age group (1. match value – final value as a percentage of the total intensity spectrum selected by participants; 2. completion time – average time to match each modality pair; 3. reference cue replayed – average number of times participants replayed the reference cue; 4. variable cue direction changes – average number of times participants adjusted to variable stimulus back and forth from increase to decrease or vice versa)

Match type	**Factor**	**Younger adults**		**Older adults (working)**		**Older adults (retired)**	
		Single-task	Dual-task	Single-task	Dual-task	Single-task	Dual-task
A-V	Match value (%)	18.3%	18.3%	15.6%	17.4%	29.5%	24.8%
	Completion time (secs)	14.31	11.67	15.1	12.14	17.2	19.18
	Reference cue replayed	2.2	2	2	1.6	2.75	1.87
	Variable cue direction change	2	1.89	1.5	1.22	1.5	1.13

T-A	Match value (%)	25.7%	23.5%	9.8%	7.8%	11.5%	12.0%
	Completion time (secs)	11.5	12.57	15.2	12.41	21.1	25.42
	Reference cue replayed	2.7	2.55	2.1	1.69	3.2	2.8
	Variable cue direction change	1.4	1.41	1.2	1.22	1.5	1.27
V-T	Match value (%)	55.7%	58.0%	61.3%	65.5%	78.6%	68.7%
	Completion time (secs)	31.7	15.59	34.0	20.53	39.2	29.21
	Reference cue replayed	4.3	3.45	3.4	1.69	4.5	3.28
	Variable cue direction change	2.0	1.81	1.5	1.22	1.6	1.43

Experimental setup and procedures

Refer to chapters 3 and 4 for detailed descriptions about the multimodal stimuli and apparatus, driving simulation (chapter 4), and experimental procedures, used in the respective studies.

Dependent measures

The dependent measures common between the single- and dual-task experiments were:

1. Response time – the time between the onset of a cue/cue combination and the time at which the participant responded to that cue/cue combination, regardless of whether the response was correct or not (in milliseconds).
2. Accuracy – the number of cue/cue combinations the participant correctly identified out of the total number of cue/cue combinations (% correct).

Signal detection theory (SDT) analysis was performed for each person and cue/cue combination. There were five possible responses to each stimulus presentation: (1) correct response ("hit"),

(2) missed signal ("miss"), (3) substitution ("miss" and "false alarm"), (4) false alarm, or (5) correct rejection where the participant did not report any signal in addition to what was actually presented. The SDT analysis measures – sensitivity (d`; a measure of the ability to discriminate a signal from noise) and response bias (β; the willingness of a person to identify a signal as a target) – were calculated.

Experimental design

For the purpose of comparing results between the two studies, a 2 (task condition: single/generic vs. dual/driving) x 3 (age group: younger, older working, older retired) x 7 (cue/cue combination) full factorial design was employed. The factor levels for cue combination were: visual (V), auditory (A), tactile (T), visual-auditory (VA), visual-tactile (VT), auditory-tactile (AT), and visual-auditory-tactile (VAT). Age was a between-subject variable, and cue combination and task condition were within-subject variables.

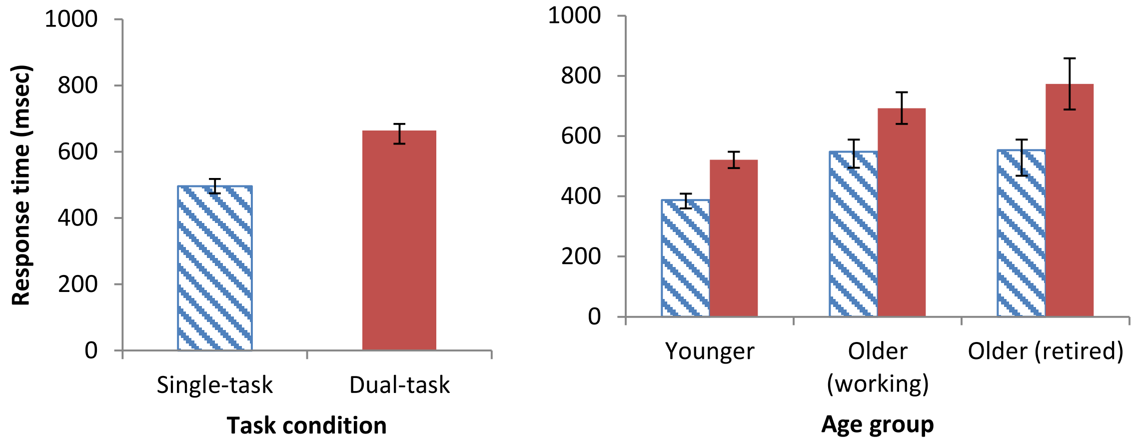
Results

A mixed-model repeated measures analysis of variance (ANOVA) was conducted to identify main and interaction effects. In addition, two-tailed Fisher's LSD post-hoc tests and paired comparisons were performed to determine differences between means for significant effects. Bonferroni corrections were applied for multiple statistical tests. Significance was set at $p < 0.05$ and partial eta squared (η_p^2) was used as a measure of effect size. Similar to the experiments in chapters 3 and 4, a standard correction method was used to calculate sensitivity (d`) and response bias (β) for signal detection analysis.

Response time

Between the two experiments, response times for accurate and inaccurate responses did not differ significantly. Overall, response time was significantly affected by task condition ($F(1, 33) = 37.965$, $p < 0.001$, $\eta_p^2 = 0.535$), age ($F(2, 33) = 7.823$, $p = 0.002$, $\eta_p^2 = 0.322$), and cue combination ($F(6, 198) = 46.775$, $p < 0.001$, $\eta_p^2 = 0.586$). There were also significant age*cue combination ($F(12, 198) = 1.905$, $p = 0.036$, $\eta_p^2 = 0.103$) and task condition*cue combination ($F(6, 198) = 5.384$, $p < 0.001$, $\eta_p^2 = 0.140$) interactions.

In particular, for the main effects, response times to cues were significantly faster for the single-task (496.11 msec, MSE = 17.12) than for the dual-task (662.29 msec, MSE = 33.34), Figure 5.1(a). This represents a 33% increase in response time for the dual (driving) task. Response times for the younger adult group (mean = 454.04 msec, MSE = 39.51) were significantly faster than for both older working (mean = 620.26, MSE = 39.51; $p = 0.016$) and older retired (mean = 663.30, MSE = 39.51; $p = 0.002$) adult groups, Figure 5.1(b). No significant difference was found between the two older adult groups. Finally, Table 5.3 summarizes the response times with associated post-hoc comparisons for each cue combination for the two tasks.



(a) (b)

Figure 5.1: Response times as a function of (a) task condition and (b) age group between single- and dual-task conditions (errors bars represent mean standard error)

Table 5.3: Post-hoc comparisons for main effect of cue combination on response time (with associated response times – RT – and p-values) combined for single- and dual-task conditions

Cue (RT in msec)	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**
V (570.90)							
A (674.46)	< 0.001						
T (585.43)		< 0.001					
VA (558.54)		< 0.001					
VT (532.81)	0.008	< 0.001	< 0.001	< 0.001			
AT (593.41)		< 0.001			< 0.001		
VAT (538.88)		< 0.001	0.020			< 0.001	

For the age *cue combination interaction, response times to all cue combinations were significantly shorter compared to the unimodal auditory stimulus for all age groups ($p < 0.001$ in all cases, see Figure 5.2 for respective response times for each group). However, in addition to this effect, for the older retired group only, response times to combined **AT** (710.26 msec, MSE = 50.44) was significantly longer than for **VA** (628 msec, MSE = 38.59, $p = 0.004$), **VT** (607.59 msec, MSE = 40.23, $p < 0.001$), and **VAT** (633.89 msec, MSE = 44.17, $p = 0.003$) – across both studies. Response times were also significantly slower for **T** (674.59 msec, MSE = 41.59) than for **VT** ($p = 0.007$) in this age group.

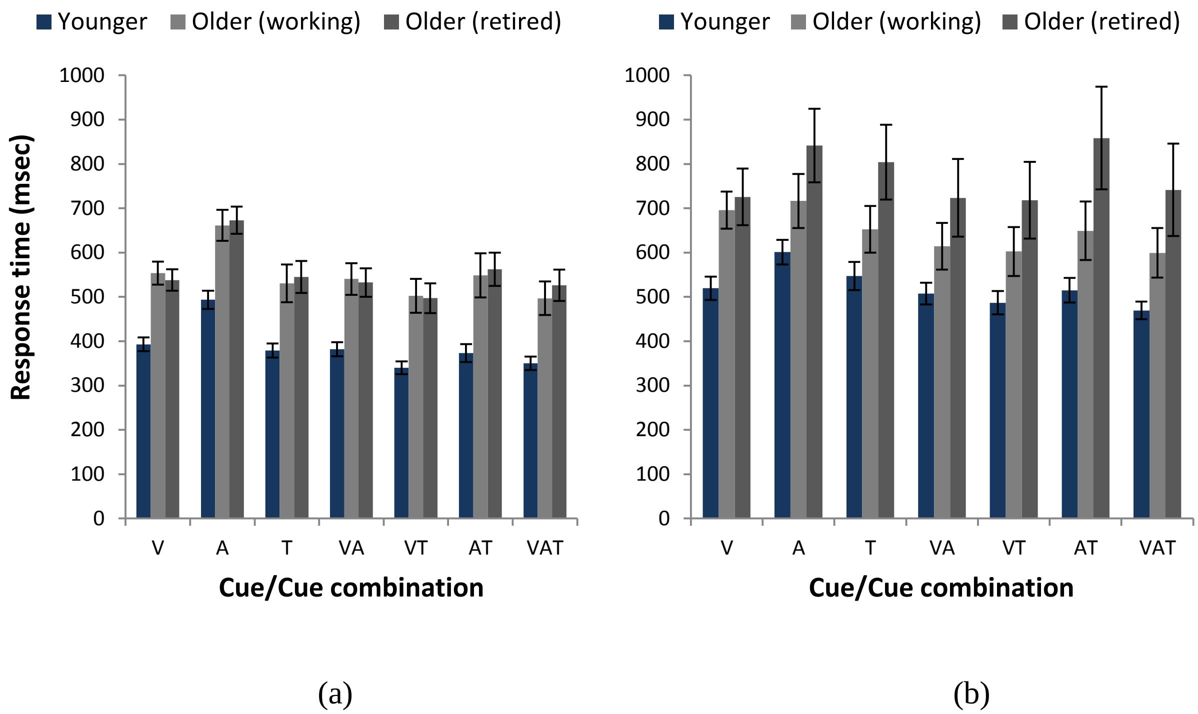


Figure 5.2: Response times as a function of age and modality/modality combination for (a) single- and (b) dual-task conditions (errors bars represent mean standard error)

For the task type*cue combination interaction, response time for each cue combination was significantly longer during the driving task, compared to the single generic task ($p < 0.001$ between all cue combinations, see Figure 5.3 for respective response times). This effect was more pronounced for cue combinations that contained a tactile signal (41.2%, 38.7%, 40% and 35.5%, respectively for T, VT, AT, and VAT).

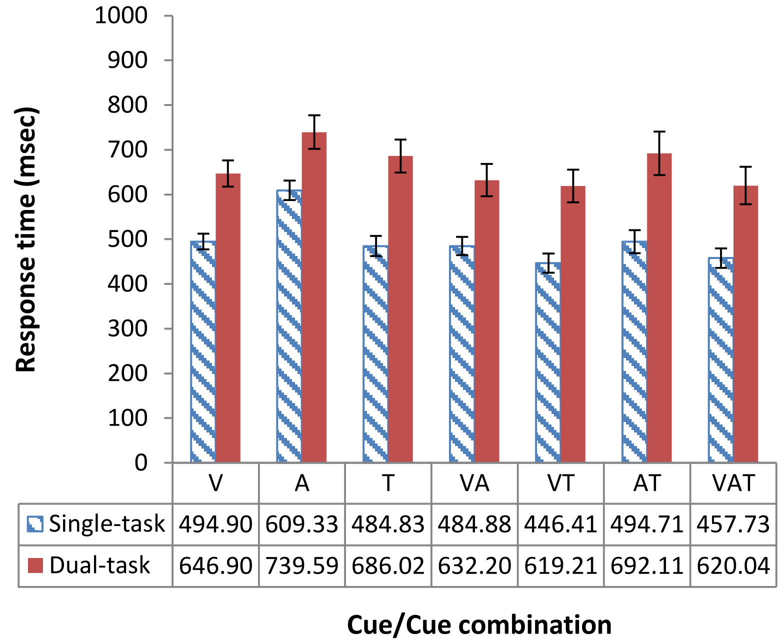
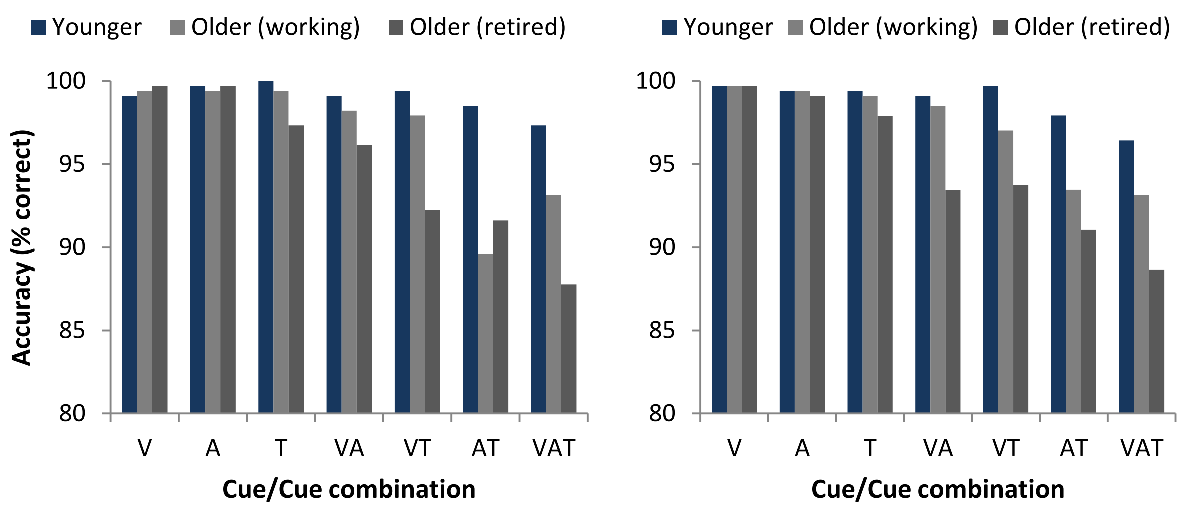


Figure 5.3: Response times as a function of modality/modality combination for the single- and dual-task conditions (errors bars represent mean standard error)

Finally, between the single- and dual-task conditions, responses times to trimodal cues (mean RT = 528.88 msec, MSE = 25.5) were significantly faster than for bimodal cues (mean RT = 561.59, MSE = 24.53), followed by unimodal cues (mean RT = 610.26, MSE = 20.79; $p < 0.001$ in all cases), across all age groups.

Accuracy

Hit rate. Hit rate was significantly affected by age ($F(2, 33) = 3.857$, $p = 0.031$, $\eta_p^2 = 0.189$) and cue combination ($F(6, 198) = 10.743$, $p < 0.001$, $\eta_p^2 = 0.246$). There was no main effect of task condition and only a marginally significant age*cue combination interaction ($F(12, 198) = 1.721$, $p = 0.065$, $\eta_p^2 = 0.094$). Retired older adults missed significantly more signals (hit rate = 95.8%, MSE = 0.9%) than the younger participants (hit rate = 99.1%, MSE = 0.9%, *p* = 0.031) – across both experiments. No difference was found between the two groups of older participants. For cue combination, between both studies, the hit rate for the **VAT** combination (92.8%, MSE = 1.4%) was lower than for all other cues/cue combinations ($p < 0.05$ in all cases, see Figure 5.4). Also, accuracy for **AT** (97.3%, MSE = 0.4%) and **VT** (97.9%, MSE = 0.5%) were both lower than for **V** (99.7%, MSE = 0.1%, $p < 0.05$ in both cases) and **T** (99.5%, MSE = 0.2%, $p < 0.05$ in both cases) alone. For the age group*cue combination interaction, in both experiments, hit rate to all bi- and tri-modal cues was significantly lower for the older retired group for the **VT**, **AT**, and **VAT** combinations, compared to the other groups.



(a) (b)

Figure 5.4: Percentage of correct responses as a function of age and modality/modality combination for the (a) single- and (b) dual-task conditions

Correct rejections. Correct rejections were not affected by task type ($F(1, 33) = 1.046$, $p = 0.314$, $\eta_p^2 = 0.031$), age ($F(2, 33) = 1.969$, $p = 0.165$, $\eta_p^2 = 0.153$), neither cue combination ($F(6, 198) = 1.724$, $p = 0.275$, $\eta_p^2 = 0.353$). Also, no interactions were observed.

Sensitivity (d`). Sensitivity was significantly affected by age ($F(2, 33) = 4.854$, $p = 0.014$, $\eta_p^2 = 0.227$) and cue combination ($F(6, 198) = 17.66$, $p < 0.001$, $\eta_p^2 = 0.349$), and marginally affected by task condition ($F(1, 33) = 3.665$, $p = 0.064$, $\eta_p^2 = 0.100$). There was also a significant age group* cue combination interaction ($F(6, 198) = 2.322$, $p = 0.008$, $\eta_p^2 = 0.123$; see Figures 5.5 and 5.6).

- *Age:* Sensitivity for the older retired group (d`= 3.847, MSE = 0.062) was lower than for the younger participants (d` = 4.121, MSE = 0.62, $p = 0.012$), but did not differ between the two groups of older participants.
- *Cue combination:* With respect to cue combination, sensitivity for **VAT** (d` = 3.696, MSE = 0.067) and **AT** (d` = 3.773, MSE = 0.077) were significantly lower than for all other signals (mean d` = 4.12, MSE = 0.04, $p < 0.05$ in all cases), but did not differ from one-another.
- *Task condition:* Sensitivity was also lower in the dual-task condition (d` = 3.963, MSE = 0.042) than in the single-task condition (d` = 4.021, MSE = 0.036).
- *Age*cue combination interaction:*
    - For the **VT** combination, sensitivity for the older retired adults (d` = 3.727, MSE = 0.097) was lower than for both the younger (d` = 4.188, MSE = 0.097, $p = 0.006$) and older working (d` = 4.072, MSE = 0.097, $p = 0.049$) participants.
    - For the retired older adults, sensitivity values for **VAT** (d` = 3.522, MSE = 0.116) and **VT** (d` = 3.727, MSE = 0.097) were both lower than for **V** and **T** (d` = 4.176 and 4.009, MSE = 0.021 and 0.067, respectively for **V** and **T**, $p < 0.01$ in both cases), and **VAT** was different from **A** (d` = 4.013, MSE = 0.099,

$p < 0.005$). Sensitivity for **VA** (d` = 3.836, MSE = 0.090) was also less than for **V** (d` = 4.176, MSE = 0.021, $p = 0.015$).

  - Within the older working group, sensitivity for **VAT** (d` = 3.631, MSE = 0.116) and **AT** (d` = 3.620, MSE = 0.133) was lower than for all other stimuli (mean d` = 4.162, MSE = 0.075, $p < 0.01$ in all cases). However, VAT and AT were not different from one-another.

Response bias (β). There was a significant main effect of age ($F(2, 33) = 5.331$, $p = 0.01$, $\eta_p^2 = 0.244$) and cue combination ($F(6, 198) = 18.841$, $p < 0.001$, $\eta_p^2 = 0.363$) on response bias. Response bias was not affected by task condition. There was also a significant age group*cue combination interaction ($F(12, 198) = 2.674$, $p = 0.002$, $\eta_p^2 = 0.139$; Figures 5.5 and 5.6).

- *Age:* Response bias for the older retired group (β = 1.782, MSE = 0.126) was higher than for the younger participants (β = 1.210, MSE = 0.126, $p = 0.009$), but did not differ from the older working group.
- *Cue combination:* For cue combination, response bias for **VAT** (β = 2.727, MSE = 0.277) was significantly higher than for all other signals (mean β = 1.252, MSE = 0.93, $p < 0.01$ in all cases). Response bias was also significantly higher for the **VT** pair (β = 1.474, MSE = 0.277) compared to all unimodal cues (mean β = 1.037, MSE = 0.37, $p < 0.05$ in all cases).
- *Age*cue combination interaction:*
  - Finally, response bias for the **VA**, **VT**, and **VAT** combinations was significantly higher for older retired adults compared to younger participants (For **VA**: β = 2.330 and 1.066, $p = 0.038$, respectively for older retired and

younger participants; For **VT**: β = 1.992 and 1.033, $p = 0.009$; For **VAT**: β = 3.595 and 1.825, $p = 0.04$).

- Within the older retired group, response bias for **VAT** (β = 3.595, MSE = 0.479) was higher than for all other stimuli (mean β = 1.31, MSE = 0.129, $p < 0.05$) except **VA** (β = 2.33, MSE = 0.339, $p = 0.447$). However, for this same group, **VA** and **VT** (β = 1.992, MSE = 0.211) were both different from **V** (β = 1.014, MSE = 0.055) and **A** (β = 0.996, MSE = 0.037) alone ($p < 0.01$ in all cases), and **VT** was different from **T** (β = 1.159, MSE = 0.099, $p = 0.006$).
- For the older working group, response bias for **VAT** (β = 2.760, MSE = 0.479) significantly higher than for **V** (β = 1.098, MSE = 0.055), **A** (β = 1.014, MSE = 0.037), **T** (β = 0.978, MSE = 0.099), and **AT** (β = 1.305, MSE = 0.227).

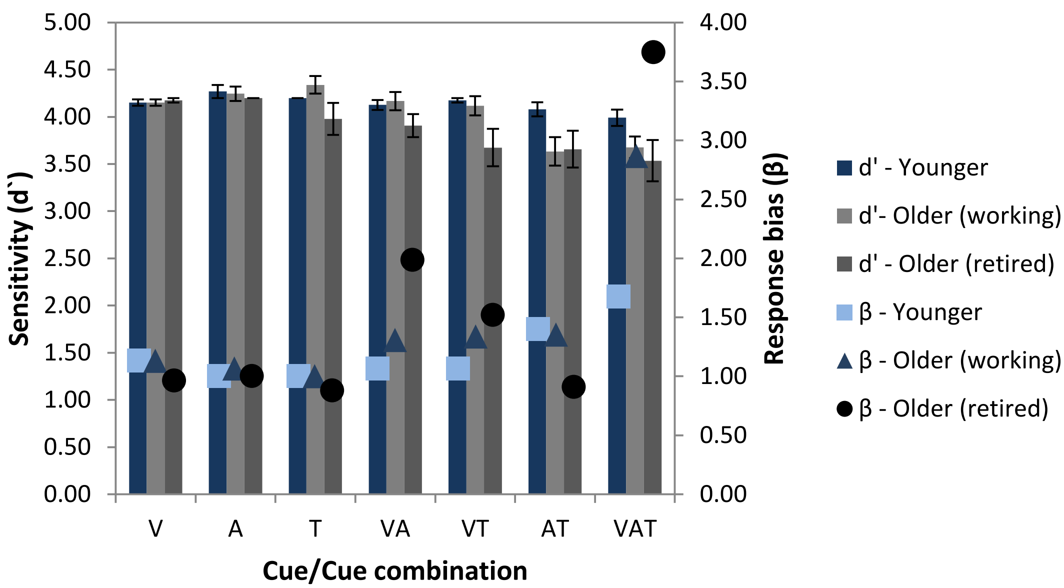


Figure 5.5: Sensitivity (d`; bars) and response bias (β, shapes inside of bars) as a function of age and modality/modality combination for single-task condition (errors bars represent standard error)

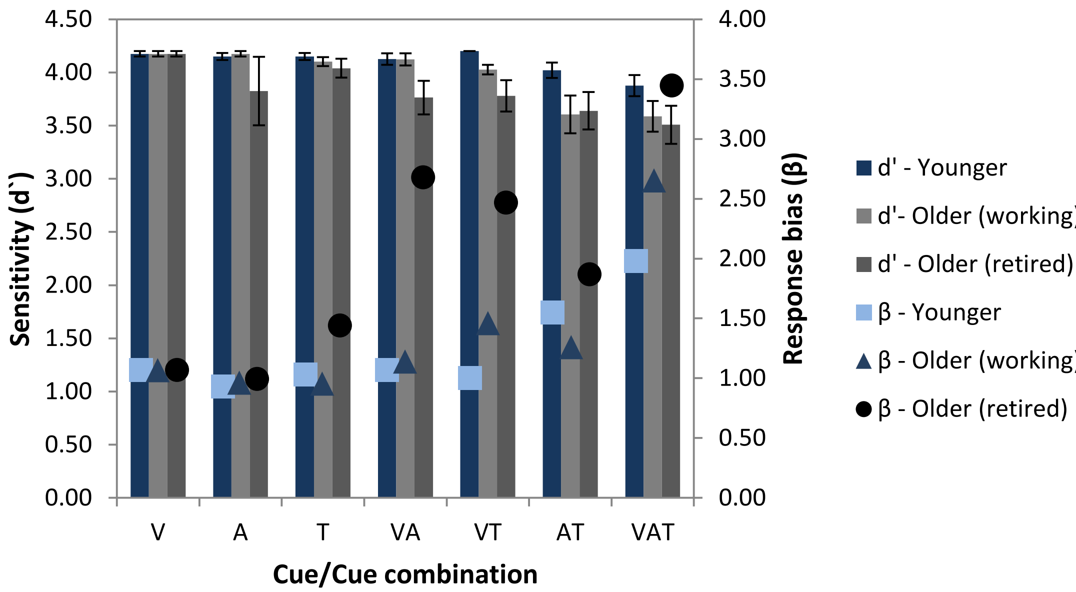


Figure 5.6: Sensitivity (d`; bars) and response bias (β, shapes inside of bars) as a function of age and modality/modality combination for dual-task condition (errors bars represent standard error)

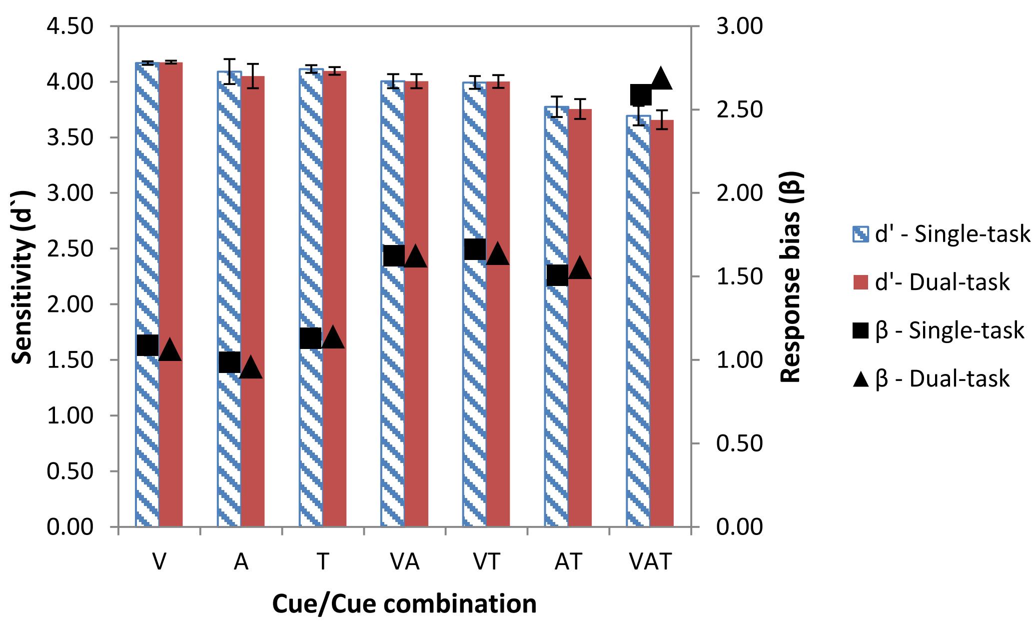


Figure 5.7: Sensitivity (d`; bars) and response bias (β, shapes inside of bars) as a function of modality/modality combination combined for single- and dual-task conditions (errors bars represent standard error)

Comparison between single- and dual-task studies. Tables 5.4- 5.6 show the breakdown for all recorded responses for each group between the two experiments. Correct responses are highlighted in green.

Table 5.4: Responses for younger adult group for (a) the single-task (23 incorrect responses of 2,351 cues) and (b) the dual-task conditions (28 incorrect responses of 2,352 cues)

(a)

Cues	Responses							
	V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	333							3
A	1	335						
T			336					
VA		1		332	2			
VT	1				334	1		
AT		4	1			331		
VAT				2	7		327	

(b)

Cues	Responses							
	V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	335							1
A	2	334						
T			334			1		1
VA	1			333	1	1		
VT					335		1	
AT		4	3			329		
VAT				3	8	1	324	

The following differences in incorrect responses were observed for the younger adult group between the two experiments:

- Number of misses (slightly) increased from 19 to 22
- Number of additions (slightly) increased from 0 to 2
- Number of substitutions remained constant: 4

The results of the driving simulation study mirrored those of the single generic detection task, Table 5.4. In particular, in the driving study, the largest number of errors occurred for pairs (i.e., VA, VT, and AT) and triplets (i.e., VAT) of multimodal stimuli (39% and 43%, respectively, compared to 43% and 39% in the single-task condition). For pairs, participants missed signals involving AT. However for triplets, the most common error was omitting the auditory cue (A), when it was combined with vision (V) and touch (T).

Table 5.5: Responses for older (working) adult group for (a) the single-task (77 incorrect responses of 2,352 cues) and (b) the dual-task conditions (66 incorrect responses of 2,351 cues)

(a)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	334							2
	A		334	1					1
	T	1	1	334					
	VA	5			330		1		
	VT	5				329	1	1	
	AT		11	1			301	22	1
	VAT	1			13	7	2	313	

(b)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	335							1
	A	1	334				1		
	T		1	333			1		1
	VA	3	1		330			1	
	VT	5		4		326		1	
	AT		12		1		314	9	
	VAT	1			18	4		313	

For the older (working) adult group, the following differences in incorrect responses were recorded between the single- and dual-task experiments:

- Number of misses (slightly) increased from 49 to 50
- Number of additions decreased from 23 to 13 (43% decrease)

- Number of substitutions (slightly) decreased by from 5 to 3

Similar to the younger group, older working individuals responded incorrectly more often to doubles and triplets, compared to singles, Table 5.5. They reported false alarms in 56% and 35% of cases for doubles and triplets, respectively. Overall, these results were similar to those observed for the single task. For pairs, most errors (57%) occurred for the AT combination. While driving, participants most often failed to report the A (55% of AT misses) while, in the generic task condition, for the same AT pair, participants falsely reported a V (63% of the cases), even though none was present. For the VAT combination, on the other hand, more than 70% of the errors involved participants missing the T. Substitutions contributed to a relatively small percentage (16%) of incorrect responses.

Table 5.6: Responses for older (retired) adult group for (a) the single-task (119 incorrect responses of 2,347 cues) and (b) the dual-task conditions (122 incorrect responses of 2,346 cues)

(a)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	334			1				3
	A		335	1					
	T			327			9		
	VA	10	2		323			1	
	VT	6		1		309	5	12	
	AT		2	5		1	306	20	
	VAT				28	11		294	

(b)

		Responses							
		V	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
Cues	**V**	334							1
	A		333				3		
	T			328			1		6
	VA	19	2		313	1			
	VT	18				314	1	1	1
	AT		10	1	1		305	16	2
	VAT	1			26	10	1	297	

For the older (retired) adult group, the following differences in incorrect responses were recorded between the generic detection task and the driving experiment:

- Number of misses increased from 67 to 98 (32% increase)
- Number of additions decreased from 43 to 21 (51% decrease)
- Number of substitutions (slightly) increased from 1 to 3

The older retired group also gave more incorrect responses for doubles and triplets, Table 5.6. Individuals in this category provided inaccurate responses to 60% of doubles and 31% of triplets. For pairs, 90% and 86% of errors for VA and VT, respectively, involved participants responding only with V (compared to 77% and 55% in the single-task condition). For AT, 53% of errors now consisted of falsely reporting V even though it was not present (compared to 71% in the previous study) – an 18% reduction. For the VAT combination, participants again omitted the T in 72% of those cases when it was presented with V and A (compared to 68% in the single-task experiment).

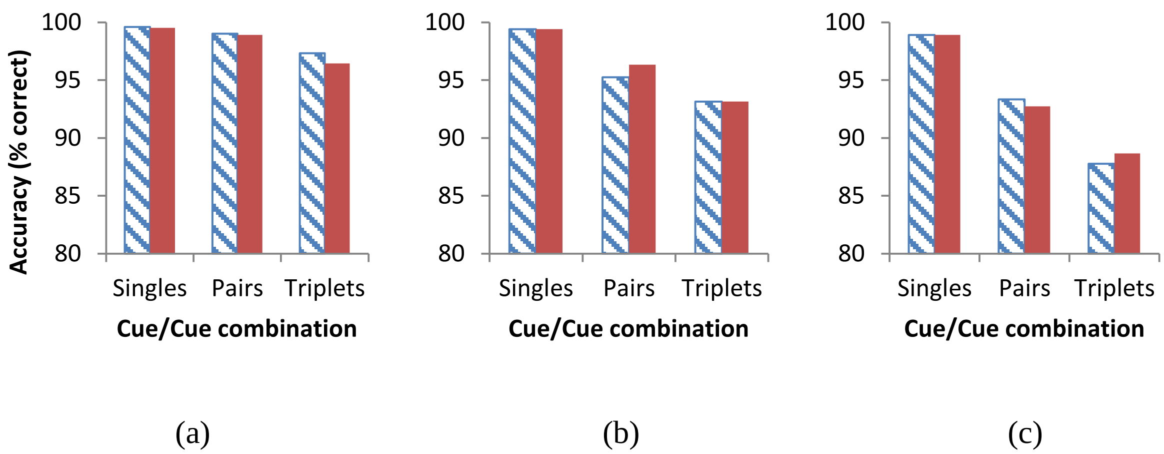


Figure 5.8: Percentage of correct responses comparison between single- and dual-task conditions for (a) younger, (b) older working, and (c) older retired age groups (blue bars: generic task, red bars: driving task)

Table 5.7: Summary of significant main and interaction effects, and post-hoc comparisons for response time and accuracy for task condition, age, and cue modality/modality combination (RT – response time; Signal detection measures: P(H) – hit rate; P(CR) – correct rejection; d` - sensitivity; β – response bias)

Metric	Task condition	Age	Cue combination	Interaction
RT	**Single < dual** --- *F*(1, 33) = 37.965, *p* < 0.001	**Younger < older working & retired** --- *F*(2, 33) = 7.823, *p* = 0.002	**A > all combinations; VT < V, T, VA, AT, & VAT; VAT < T** --- *F*(6, 198) = 46.775, *p* < 0.001	**T, VT, AT, and VAT greatest increase from single to dual task** --- *Task condition* cue combination*: *F*(12, 198) = 5.384, *p* < 0.001 **(1) unimodal A > than all combinations (for all age groups) and (2) for older retired group AT > VA, VT & VAT and T > VT** --- *Age group*cue combination*: *F*(12, 198) = 1.905,*p* = 0.036
P(H)	Not significant	**Older retired < younger** --- *F*(2, 33) = 3.857, *p* = 0.031	**VAT < all combinations; AT & VT < V & T** --- *F*(6, 198) = 10.743, *p* < 0.001	**VT, AT, & VAT lower for older retired than other groups** --- *Age group*cue combination*: *F*(12, 198) = 1.721, *p* = 0.065
P(CR)	Not significant	Not significant	Not significant	Not significant

d`	**Dual < single** **---** $F(1, 33) = 3.665$, $p = 0.064$	**Older retired < younger** **---** $F(2, 33) = 4.854$, $p = 0.014$	**VAT & AT < all combinations** **---** $F(6, 198) = 17.66$, $p < 0.001$	**(1) VT lower for older retired than for younger and older working, (2) for older retired – VAT < V & T; VAT < A; VA < V, and (3) for older working – VAT & AT < all combinations** **---** *Age group*cue combination*: $F(12, 198) = 2.322$, $p = 0.008$
β	Not significant	**Older retired > younger** **---** $F(2, 33) = 5.331$, $p = 0.014$	**VAT > all combinations; VT > other bimodal cues** **---** $F(6, 198) = 18.841$, $p < 0.001$	**(1) VA, VT & VAT greater for older retired than younger, (2) for older retired –VAT > all combinations (except VA); VA & VT > V & A; VT > T, and (3) for older working – VAT > V, A, T & AT** **---** *Age group*cue combination*: $F(12, 198) = 2.674$, $p = 0.002$

Discussion and Conclusion

The studies presented in chapters 3 and 4 examined how reliably and accurately younger and older adults can perceive and process non-redundant multimodal cues, either in isolation or when performing a concurrent driving task. The purpose of this chapter is to compare and contrast the findings from these two experiments. The sections below discuss differences and similarities between the experiments. (Refer to respective chapters for more thorough explanations of findings).

In summary, both experiments confirm that people are more likely to miss information if multiple unrelated signals are presented in parallel in different sensory channels. As expected, this effect was most pronounced for triplets and in older retired adults. The findings from the two studies differ in that response times to cues were longer in the dual-task condition, and also increased by the largest percentage for stimuli involving the sense of touch.

The ultimate goal of this work is to address these performance decrements by developing adaptive displays that will likely benefit older adults in particular. Chapter 6 will report on a study that evaluates one means of adapting information presentation, namely adjusting the timing of presentation of multimodal cues. The study focused on the older retired participants as they contributed to the largest percentages of errors in the single- (generic) and dual- (driving) task experiments.

Differences between the single- (chapter 3) and the dual-task (chapter 4) conditions

As expected, the dual-task condition resulted in significantly longer response times, compared to the single detection task. This difference can be attributed to the increased task interference associated with the driving task. In the single-task experiment, participants' sole task was to monitor for, and respond to, each signal. In contrast, in the dual-task study attentional resources were now consumed by the continuous visuo-spatial task of driving the vehicle which, according to Multiple Resource Theory (MRT), may have resulted in resource competition, both in terms of modality (vision), processing stage (perception, cognition, and response) and response type (manual responses both for driving and reporting cue detection; Wickens 1980, 1984, 2002, 2008). This finding may also be explained in terms of a speed-accuracy trade-off (e.g., Wickens, Lee, Liu, & Gordon-Becker, 1998). Having completed the single-task experiment and being familiar with its purpose, the increased task demands may have driven participants to focus on correctly identifying each cue/cue combination, at the expense of being quick to respond.

For all age groups, response times in the driving study increased the most for combinations that contained a tactile signal. This may be explained using the MRT framework. In this particular case, both processing stages, i.e., the perception of the signal and the response to the signal, involved the same modality (Wickens, 2008), thus resulting in resource competition. MRT posits that the ability to perform two tasks in parallel will be reduced if both tasks share the same processing stage (perception/cognition/response), code (spatial/verbal), or modality (visual/auditory/tactile). Wolffelaar, Rotthengatten, & Brouwer (1991) also reported interference with manual responses during a simulated driving task. They found that performance on the task was significantly improved once participants were instructed to give verbal responses instead.

Similarities between the single- and the dual-task conditions

These findings were discussed in more detail in previous chapters (3 and 4):

- Across all three age groups, response times to triplets were shorter than for pairs, followed by single stimuli
- Older adults responded more slowly to all cue combinations, as compared to younger adults
- The percentage of substitutions was negligible (6% across all trials)
- Hit and miss rates were essentially the same. One likely explanation for this finding is a ceiling effect due to the nature of the driving task. It did not involve surrounding traffic, additional road scenery, or additional sounds/vibrations. Also, pairwise comparisons for each individual did not reveal significant differences between the two experiments
- For all age groups in both experiments, response times to the unimodal auditory stimuli were significantly slower than for all other stimuli. Traditionally, the auditory modality is responded to faster than visual stimuli (e.g., Scott & Gray, 2008; Hecht, Reiner, & Karni, 2008a, 2008b). However, during this experiment, pink background noise was played continuously over the stereo headphones. This may have caused a slight processing delay due to having to discriminate the signal from background noise

- Older participants more often reported only V when presented with VA and VT pairs (presence of visual dominance)
- Attentional blink, when the second of the two signals is missed because they are presented in too close temporal proximity of one-another, is suggested to have been present in both studies
- In both experiments, the older working and retired groups tended not to report the tactile signal (T) when it was presented simultaneously with visual (V) and auditory (A) stimuli (in approximately 68% of all errors for this condition)
- Another common error observed in the single- and, to a lesser extent, the dual-task experiment was the false reporting of a V when presented with only AT

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CHAPTER 6

Development and Evaluation of a Countermeasure to Breakdowns in Multimodal Information Processing in Older Adults

Multimodal information presentation (e.g., the distribution of information across sensory channels) has been shown to support a number of functions, such as reducing visual data overload and facilitating more effective interruption and attention management (Brickman, Hettinger, & Haas, 2000; Calvert, Spence, & Stein, 2004; Latorella, 1999). However, limitations of this approach are not well understood. The studies reported in chapters 3-5 represent important first steps towards identifying potential limits of multisensory information processing. They demonstrated difficulties with detecting and processing pairs and, even more so, triplets of non-redundant multimodal signals. Specifically, participants occasionally failed to notice a tactile signal when it was combined with a visual and auditory cue, and they falsely reported a visual signal when presented with an auditory-tactile pair. These difficulties were observed mostly in older adults who were also slower to respond to multimodal cues/cue combinations, compared to their younger counterparts. During multitasking (driving and detection of multimodal signals), older adults also displayed greater deviations in lateral lane position and lateral velocity after being presented with multimodal cue combinations. Finally, for both the younger and older adult groups, deviations in speed were highest after having being presented with a combined visual-auditory-tactile (VAT) triplet.

The observed performance decrements highlight perceptual and cognitive limitations that need to be addressed to ensure the robustness of multimodal displays. As previewed in the Introduction, one possible countermeasure to these performance breakdowns is adaptive display design where the timing, salience, amount, modality, location, or frequency of signals may be adjusted to account for changing contexts (such as different users or cue combinations; e.g., Hameed & Sarter, 2009; Parasuraman et al., 1992; Parasuraman, Cosenzo, & De Visser, 2009). These adjustments are expected to increase the likelihood that all cues are reliably perceived and processed.

The goal of this final study was to implement and evaluate one particular type of adaptive multimodal display where the timing of signals is adjusted to avoid concurrence which, as discussed earlier, can result in masking and lead to poor detection performance due to visual dominance. The effectiveness and feasibility of this approach was tested in the same driving environment employed in chapter 4. The current study focused on older retired adults, since accuracy was significantly worse in this group, compared to the older working and younger participants.

Our expectations were that: (1) delaying 1 or more signals in pairs and triplets would increase the hit rate, (2) presenting the visual cue second and the tactile cue first (in cue combinations) would eliminate sensory dominance and masking effects, and (3) performance on the driving task would improve as participants struggle less and have slightly more time to process the combined multimodal cues. Response time was not expected to change since participants were again instructed to respond as soon as any stimulus was perceived.

Methods

Participants

Six participants from the older retired adult group in the previous two experiments were asked and volunteered to take part in this study. Their average age was 68.5 years (SD = 2.74; range = 65-72). These individuals were selected because, in the previous driving study, they provided the largest number of inaccurate responses. The requirements for participation were the same as in the previous experiments (i.e., valid U.S. driver's license, normal to corrected-to normal vision, no hearing impairments, and no compromised sense of touch). All 6 participants gave informed consent and were compensated at a rate of $80/hour. In addition, the top performing participant received an additional $20 as an incentive for outstanding performance. This was done to ensure that participants assign the same priority to both tasks, rather than focus on one task alone.

Driving Simulation

The experiment was conducted using the same fixed-based medium-fidelity desktop driving simulation, STISIM Drive™, described in chapter 4 (and shown in Figures 4.1- 4.3). Participants manipulated a Logitech force-feedback steering wheel and associated floor-mounted throttle and brake pedals to drive the simulated vehicle. The driving environment consisted of a standard roadway, without surrounding traffic, other road scenery, sounds, or vibrations. The simulation displayed a two-lane highway (opposite directions; each lane was 12 feet) that was primarily comprised of straight sections and frequent, but moderate road curvatures (suggested driving speeds between 45-50 mph). In addition, in-vehicle displays included standard analog speedometer and RPM gauges, a digital gear indicator, and an elevated rear-view mirror. As in the previous study, the highway consisted of a total of 30 curves, which could be negotiated without having to change the speed of the vehicle. The sampling rate of the simulation was 15 Hz.

Multimodal stimuli and apparatus

The stimuli and apparatus in this study were identical to those used in the previous experiment (chapters 2-4): visual stimulus (blue LED light; luminance range: 0-126.77 cd/m^2; located at an angle of approximately 35 degrees (10.5 inches) below the center of a 30" computer monitor), auditory cues (350-Hz monotone beeps; loudness range: 0-88 dB) and tactile cues (vibrations presented at 250 Hz using C-2 "tactors," signal gain range: 0-18 dB). Two adjacent tactors were attached to the back/middle of a Velcro belt fastened around participants' waist, over clothing, in direct contact with the skin. Pink noise was played over the stereo headphones to eliminate any audible sounds associated with the tactor vibrations. Overhead room lighting was turned off during the experiment.

Countermeasures and experimental design

The countermeasure to observed performance breakdowns in the previous experiment consisted of introducing a stimulus-onset asynchrony (SOA; time between the onset of two signals) of 500 milliseconds (msec) between the two stimuli in multimodal pairs (see Figure 6.1). In the case of triplets, two signals were presented simultaneously, while the third was presented with a 500-msec delay. This SOA was chosen for two reasons. First, the phenomenon of crossmodal attentional blink has been observed when visual and auditory stimuli are separated by 50-250 msec (Arnell & Jolicoeur, 1999; Martens & Johnson, 2005; Wickens & Hollands, 2008) and up to 450 msec for visual-tactile pairs (Soto-Faraco et al., 2002). Second, the fastest response time to cues that involved touch for any participant in the older retired group was 552 msec. Therefore, the SOA had to be between these two extremes (450-552 msec) to avoid attentional blink and prevent participants from responding to the first cue before the second signal was presented.

The visual cue (**V**) was always presented in the last position (i.e., A–**V**, T–**V**, and TA–**V**). This was done to avoid visual dominance effects on signals in the other sensory channels (Colavita, 1974; Sinnett, Spence, & Soto-Faraco, 2007). Also, the tactile signal (**T**) was always presented first (i.e., **T**–V, **T**–A, and **T**A–V) to prevent forward masking involving the sense of touch. Craig & Evans (1987) & Soto-Faraco et al. (2002) demonstrated interference when randomly blocked tactile signals were presented second, as opposed to first.

In summary, the study employed a single within-subject factor design: cue combination. The final 7 combination levels for this factor (in the respective modality order; SOA denoted by hyphen) were: visual (V), auditory (A), tactile (T), auditory–visual (A–V), tactile–visual (T–V), tactile–auditory (T–A), and tactile/auditory–visual (TA–V). All dependent measures (response times, accuracy, and driving performance) in the current experiment were compared to those in the previous driving experiment (chapter 4). Therefore, parts of the analysis used a 2 (signal timing) x 7 (cue combination) design. Signal timing was also a within-subject variable with factor levels: concurrent and offset.

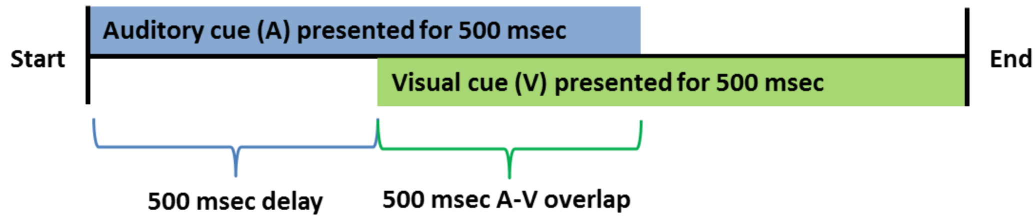

Figure 6.1: Illustration of 500-msec timing delay between auditory and visual combination (total duration of A–V combination = 1500 milliseconds)

Experimental task and procedure

Participants first signed the consent form and were reminded about the purpose of the experiment. Next, participants were introduced to the full range of multimodal stimuli they could use in the subsequent crossmodal matching task. Each participant performed crossmodal matching using the same keyboard arrows method described in chapter 2 and employed in chapters 3 and 4 to ensure that the visual, auditory and tactile cues were perceived as equal in terms of stimulus intensity. These values they selected were used for the remainder of the experiment. Table 6.1 provides a summary of the final values selected by participants.

Table 6.1: Crossmodal matching outcomes for 6 participants for the concurrent and offset signal timing experiments (1. match value – final value as a percentage of the total intensity spectrum selected by participants; 2. completion time – average time to match each modality pair; 3. reference cue replayed – average number of times participants replayed the reference cue; 4. variable cue direction changes – average number of times participants adjusted variable stimulus back and forth from increase to decrease or vice versa)

Match type	Factor	Concurrent	Offset
A-V	Match value (%)	29.9%	33.2%
	Completion time (secs)	16.17	15.12
	Reference cue replayed	1.83	2.13
	Variable cue direction change	1.0	1.03
T-A	Match value (%)	13.73%	20.4%
	Completion time (secs)	24.6	17.22
	Reference cue replayed	2.83	2.87
	Variable cue direction change	1.33	1.17
V-T	Match value (%)	71.4%	71.6%
	Completion time (secs)	31.17	28.54
	Reference cue replayed	2.9	3.0
	Variable cue direction change	1.47	1.53

Next, participants repeated the three training sessions they were exposed to in experiment 2 (chapter 4). This was done to familiarize them with the tasks and required responses.

1. *Detection task*: participants were presented with a total of 28 cues (4 of each cue combination) that appeared every 7 seconds. They were asked to press a button on either side of the steering wheel and then verbalize the cue(s) detected, in the order perceived. Participants were reminded that they should not look directly at the light. A performance score of 90% was required to proceed to the next training phase.
2. *Driving task*: for the second training task, participants were reintroduced to the simulated vehicle and associated controls and procedures and asked to position themselves comfortably in front of the driving simulator. Next, they were reminded of

their tasks: to (1) keep a constant speed of 40 mph (58.67 ft/s) and to (2) remain in the center of the lane (6 feet) at all times during the scenario. On a case-by-case basis, the experimenter determined whether participants needed to repeat the practice driving task. Here, participants were required to demonstrate that they could perform the task with an average speed and lane position within 5% of the requirements.

3. *Driving and detection task:* this final part of the training session combined the two tasks, where participants were instructed that they should not prioritize one task over the other.

For the experiment, participants were presented with 28 instances of each cue combination, while driving the simulated vehicle. This resulted in a total of 196 trials per person. Each participant was exposed to 49 cues in 4 separate blocks that lasted about 5 minutes each. In these blocks, cues/cue combinations were presented on average once every 7 seconds (range 4-10 seconds). The duration of unimodal stimuli was 1 second and 1.5 seconds for bi- and trimodal signals (due to the SOA of 500 msec). As in the training, they were instructed to press a designated button on either side of the steering wheel as soon as they "saw and/or heard and/or felt." They were asked to then verbally indicate the modality of cue(s) that they detected (using any phrasing of their choice, such as light, sound/tone, vibration/touch/buzz/back), in the order perceived. The order in which the cue combinations were presented was counterbalanced and was different from the order of those presented in the experiment in chapter 3. Following the experiment, participants completed a debriefing session (full debriefing questionnaire can be seen in Appendix 1C). Altogether, the experiment lasted approximately 1.5 hours.

Dependent measures

The dependent measures in this study are the same as those in the previous study (chapter 4), including response times, accuracy (signal detection analysis):

1. Response time – the time between the onset of a cue/cue combination and the time at which the participant responded to that cue/cue combination (in milliseconds)
    2. Accuracy – the number of cue/cue combinations the participant correctly identified out of the total number of cue/cue combinations (% correct)
        a. *Signal detection theory* – Correct response (hit), missed signal (miss), substitution (miss or false alarm), false alarm, correct rejection (no report of signal in addition to what was actually presented), sensitivity (d`; a measure of the ability to discriminate a signal from noise), and response bias (β; the willingness of a person to identify a signal as a target).

The following driving performance measures were calculated:

1. Longitudinal velocity (FV) – the forward speed of the subject vehicle (feet/second)
2. Lateral velocity (LV) – the horizontal component of speed of the vehicle, with respect to the center of the lane (feet/second; positive to the right)
3. Lateral lane position (LP) – a measure of the vehicle's displacement from the center of the lane, with respect to the roadway diving line (feet; 0-6 feet = right of center, 6-12 feet = left of center)
4. Steering wheel angle (SWA) – a measure of the steering wheel displacement from the initial resting position in a circular direction (degrees; positive to the right)

As in chapter 4, the goal in employing the above metrics was to determine whether the processing of cue combinations affected driving performance. For each measure, we calculated the absolute deviations (magnitude of deviations in either direction) for both 3 seconds before and 3 seconds after the start of a cue/cue combination (see Figure 4.5 in chapter 4 for an illustration of concept).

Results

Due to the relatively small number of participants ($n = 6$) used in this study, paired t-tests were used to identify significant differences between means. Significance was set at $p < 0.05$. Also, as a result of the smaller sample size, several measures were found to be marginally significant ($0.10 > p > 0.05$). Similar to the experiments in chapters 3 and 4, a standard correction method was used to calculate sensitivity (d\`) and response bias (β) for signal detection analysis.

Response time

Adjusting the timing of cues did not affect response time ($t(5) = 0.770$, $p = 0.476$) to the various cue combinations (see Figure 6.2). There was no significant difference between singles, pairs, and triplets. Also, response times for accurate and inaccurate responses did not differ significantly.

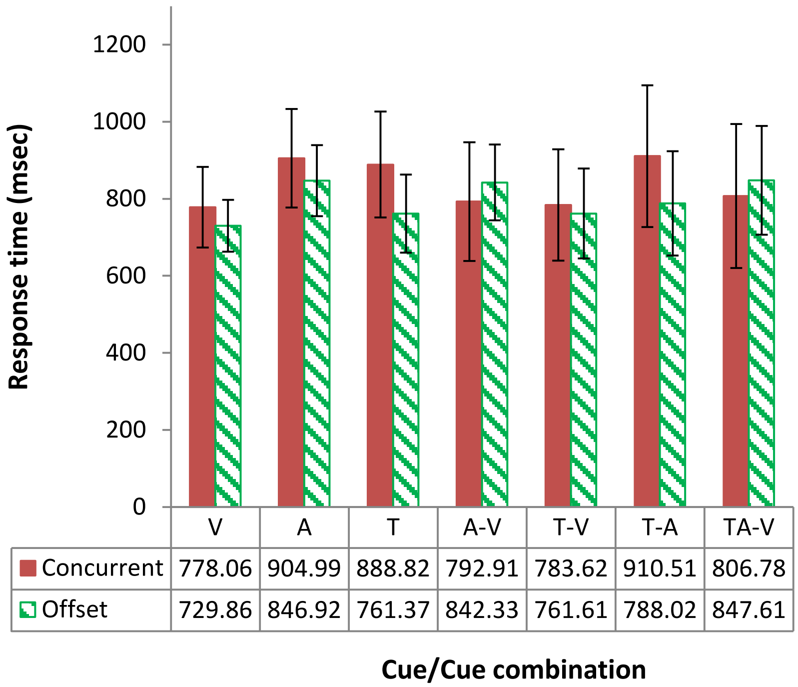

Figure 6.2: Response times as a function of modality/modality combination for concurrent and offset signal timing conditions (errors bars represent mean standard error)

Accuracy

Signal detection analysis. Hit rate (accuracy) was marginally higher when the cues were offset, compared to in the concurrent driving study ($t(5) = -2.127$, $p = 0.087$), see Figure 6.3. In particular, hit rate improved for **T–V** (hit rate (offset signal timing) = 96.7% (MSE = 1.75%) versus hit rate (concurrent signal timing) 89.3%, (MSE = 3.45%); $t(5) = -2.148$, $p = 0.084$) and **T–A** (hit rate (offset signal timing) = 99.4% (MSE = 0.59%) versus hit rate (concurrent signal timing) 92.6% (MSE = 3%); $t(5) = -2.395$, $p = 0.062$). The hit rate for trimodal **VAT** also improved (from 80.9% to 89.2%) between the two experiments, but the difference did not reach significance due to the large standard deviation in the concurrent signal timing condition (see comparison between concurrent and offset signal timing section below for more details about responses recorded). For the offset signal timing condition only, hit rate for **VAT** (89.2%) was significantly lower than for all other cue combinations ($p < 0.05$ in all cases).

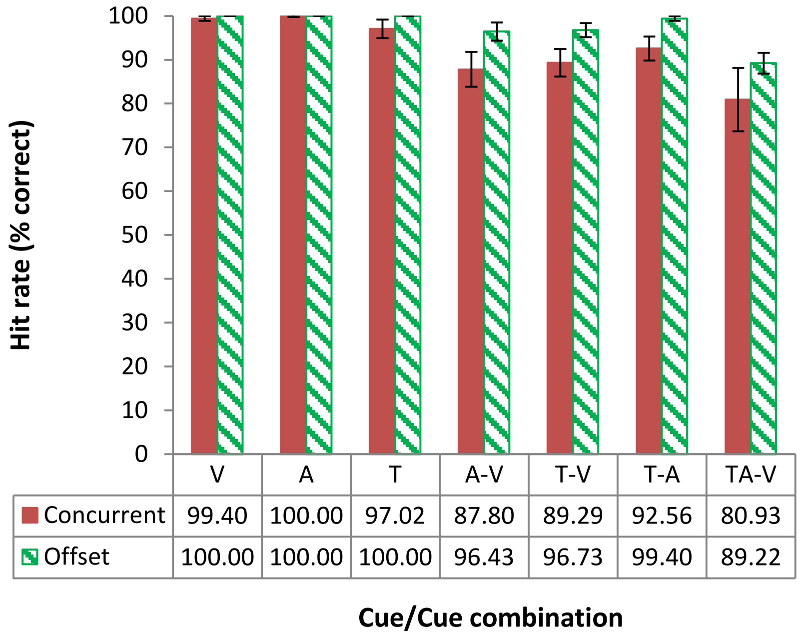

Figure 6.3: Percentage of correct responses (hit rate) as a function of modality/modality combination for concurrent and offset signal timing conditions (errors bars represent mean standard error)

Sensitivity ($t(5) = -3.990$, $p = 0.010$) and response bias ($t(5) = 4.170$, $p = 0.009$) both differed significantly between the concurrent and offset signal timing experiments. However, correct rejections did not differ between signal timing conditions ($t(5) = -0.875$, $p = 0.421$).

In particular, sensitivity for the **T–A** (d` = 3.99, MSE = 0.129) and **T–V** (d` = 3.88, MSE = 0.132) pairs in the offset signal timing experiment was greater than for **AT** (d` = 3.177, MSE = 0.215, $t(5) = -3.089$, $p = 0.027$ compared to **T–A**) and **VT** (d` = 3.41, MSE = 0.197, t(5) = -2.467, $p = 0.057$ compared to **T–V**) in the concurrent signal timing study. Likewise, sensitivity for the **A–V** pair (d` = 3.88, MSE = 0.154) was greater than for **VA** (d` = 3.38, MSE = 0.215,

$t(5) = -2.033$, $p = 0.098$). Within the offset signal timing experiment, sensitivity for **VAT** (d` = 3.29, MSE = 0.191) was significantly lower than for all other cue combinations ($p < 0.03$ in all cases).

For response bias, participants were more confident in their responses to trimodal **TA-V** (β = 3.52, MSE = 0.823) in the offset signal timing experiment compared to **VAT** (β = 5.01, MSE = 0.99, $t(5) = 4.954$, $p = 0.004$) in the concurrent signal timing study. The same trend was observed for **A–V** (β = 1.877, MSE = 0.68) compared to **VA** (β = 4.22, MSE = 0.953, $t(5) = 2.410$, $p = 0.061$). In both experiments, however, response bias for **VAT** (β = 5.01, MSE = 0.999 in concurrent signal timing and β = 3.52 in offset signal timing) was significantly higher than for all other combinations ($p < 0.05$ in all cases), except **VT** (β = 3.8, MSE = 1.01 for concurrent signal timing and β = 1.84, MSE = 0.548 for offset signal timing conditions).

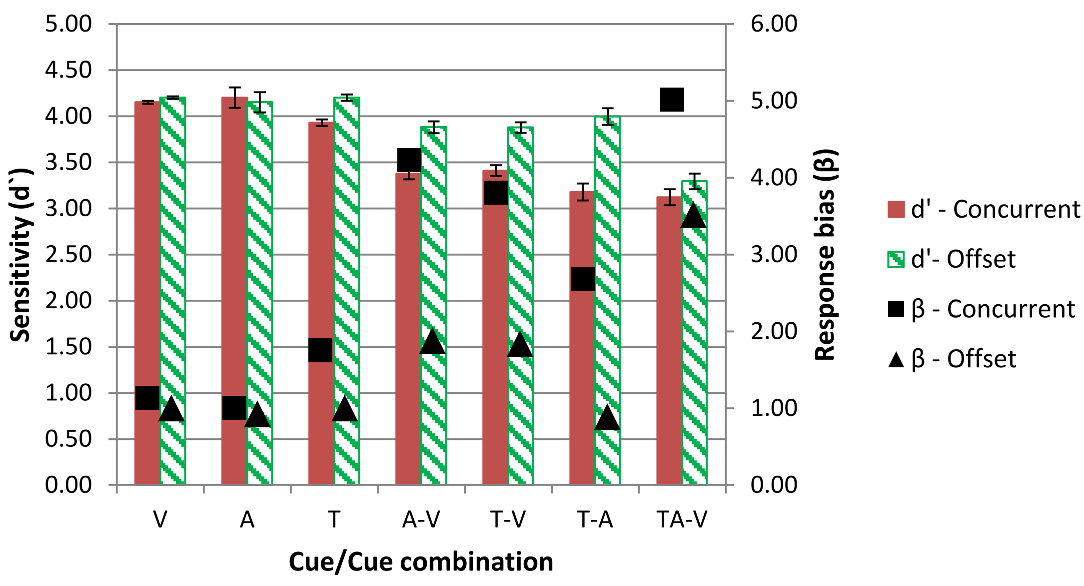

Figure 6.4: Sensitivity (d`; blue bars) and response bias (β, black squares) for 6 participants for concurrent and offset signal timing conditions (errors bars represent standard error)

Comparison between concurrent and offset signal timing conditions. Table 6.2 shows the breakdown for all recorded responses for the 6 participants between the generic task, concurrent signal timing driving, and offset signal timing driving conditions. Correct responses are shaded.

Table 6.2: Responses for 6 older retired adults only for (a) single (generic) task (90 incorrect responses of 1,170 cues), (b) concurrent signal timing (dual/driving) task (108 incorrect responses of 1,170 cues), and (c) offset signal timing (dual/driving) task (39 incorrect responses of 1,176 cues)

(a)

	Responses							
Cues	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	166							
A		167						
T			159			9		
VA	10	2		156				
VT	6		1	2	145	5	8	
AT		2	3		1	141	19	
VAT				12	7	2	146	

(b)

	Responses							
Cues	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	166							1
A		167				1		
T			161			1		5
VA	18	2		146	1			
VT	17				148		1	1
AT		9	1			139	15	2
VAT	1			21	10		135	

(c)

	Responses							
Cues	**V**	**A**	**T**	**VA**	**VT**	**AT**	**VAT**	**None**
V	168							
A		167				1		
T			168			1		
VA	4	1		161				1
VT	5				163	1	1	
AT		1				161	5	
VAT		1		9	4	4	149	

Across all three experiments, the trends for incorrect responses to the various modality combinations were the same, even though the absolute numbers differed.

For the <u>generic (single) task</u>, participants gave more incorrect responses for pairs (66%) and triples (23%), compared to singles (11%), see Table 6.2(a).

- *<u>Pairs:</u>* For VA, 83% of the incorrect responses involved participants responding only with V. For VT, there was no clear pattern for inaccurate responses. For AT, 76% of errors consisted of participants falsely reporting V even though it was not present.
- *<u>Triplets:</u>* For VAT, 57% of incorrect responses were attributed to participants omitting the T when it was presented concurrently with V and A
- *<u>Differences between the single and concurrent signal timing (dual) driving tasks</u>*:
    - Number of misses increased from 45 to 88 (96% increase)
    - Number of additions decreased from 36 to 18 (50% decrease)
    - Number of substitutions increased from 9 to 2 (78% decrease)

For the <u>concurrent signal timing driving (dual) task</u>, similar to the single task, participants gave more incorrect responses for doubles (62%) and triples (30%), compared to singles (8%), see Table 6.2(b).

- *<u>Pairs:</u>* For VA and VT, 86% and 89%, respectively, of the incorrect responses involved participants responding only with V. For AT, 54% of errors consisted of participants falsely reporting V even though it was not present.
- *<u>Triplets:</u>* For VAT, 66% of incorrect responses were attributed to participants omitting the T when it was presented concurrently with V and A.

- *Differences between the concurrent and offset signal timing driving tasks*:
    - Number of misses decreased from 88 to 30 (66% decrease)
    - Number of additions decreased from 18 to 8 (44% decrease)
    - Number of substitutions decreased from 2 to 1

For the offset signal timing driving (dual) task, participants, to a lesser extent, gave more incorrect responses for pairs (49%) and triples (46%), compared to singles (5%), see Table 6.2(c).

- *Pairs:* For VA and VT, 67% and 71%, respectively, of the incorrect responses for pairs involved participants responding only to V, whereas for AT, 83% of errors were committed by participants falsely reporting V
- *Triplets:* For VAT, 50% of incorrect responses were attributed to participants omitting the T when it was presented concurrently with V and A

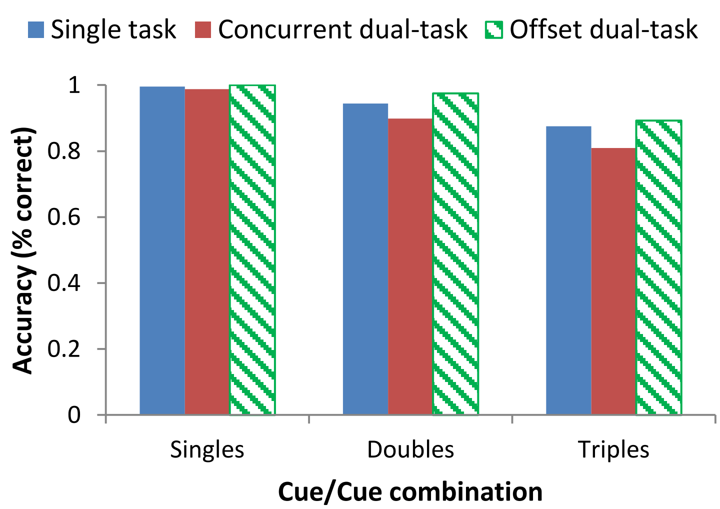

Figure 6.5: Percentage of correct responses comparison for 6 participants between single (blue bars), concurrent signal timing driving (red bars), and offset signal timing driving (green bars) task conditions

Driving performance

Participants were asked to maintain a constant speed of 40 mph (58.67 ft/s) and to keep the vehicle as close as possible to the center of the lane (lateral lane position of 6 feet). During the driving simulation, the average speed and lane position for the 6 participants was 58.02 ft/s (SD = 4.38) and 6.34 ft. (SD = 0.69), respectively, when no cue was present. As mentioned earlier, for each driving measure, the average deviation and direction of deviation 3 seconds before and 3 seconds after the initiation of a cue presentation was calculated. The sections below describe differences between the concurrent and offset signal timing driving experiments.

Velocity. After being presented with the various cue combinations, the average deviation in forward (longitudinal) velocity did not differ between the concurrent signal timing driving (1.09 ft/s, MSE = 0.141) and offset signal timing (0.82 ft/s, MSE = 0.105, $t(5) = 1.739$, $p = 0.142$) studies, Figure 6.6(a). Similarly, deviations in lateral velocity were not found to be significantly different between the two experiments (LP concurrent signal timing = 0.372 ft/s, MSE = 0.026; LP offset signal timing = 0.43 ft/s, MSE = 0.037; $t(5) = -1.399$, $p = 0.221$), Figure 6.6(b).

Lateral lane position (LP). No significant differences was found between the concurrent and offset signal timing driving experiments for changes in lane position (LP concurrent signal timing = 0.711 ft., MSE = 0.061; LP offset signal timing = 0.811 ft., MSE = 0.679; $t(5) = -0.041$, $p = 0.969$), Figure 6.6(c).

Steering wheel angle (SWA). Finally, deviations in the steering wheel angle for the concurrent signal timing driving task (angle = 5.79°, MSE = 0.541) did not differ from the driving task that involved timing adjustments (angle = 6.75°, MSE = 0.114; $t(5) = -1.231$, $p = 0.273$), Figure 6.6(d).

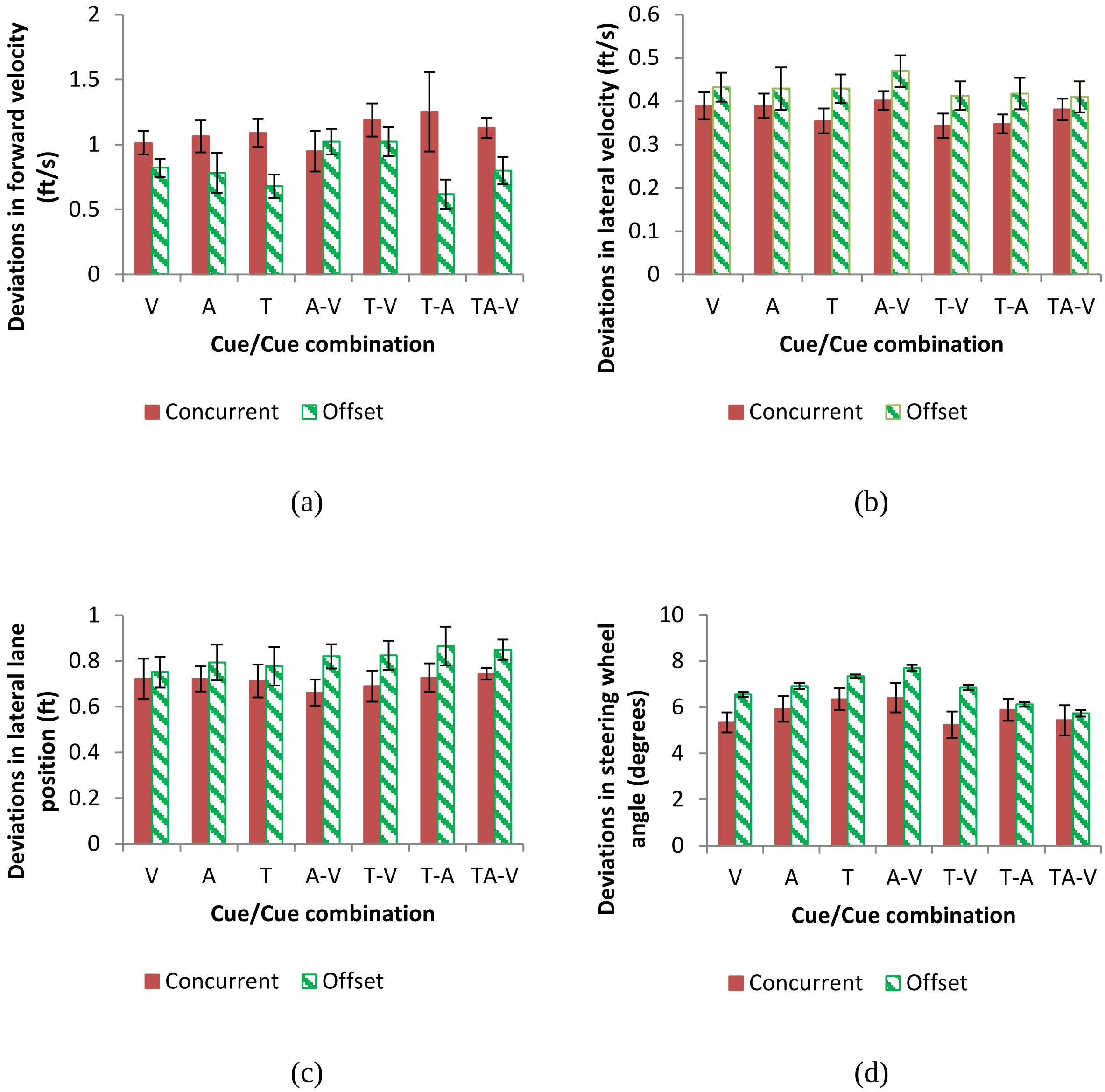

Figure 6.6: Average absolute (a) forward velocity, (b) lateral velocity, (c) lateral lane position, and (d) steering wheel angle as a function of modality/modality combination for 6 participants between the concurrent and offset signal timing driving tasks

Discussion and Conclusion

Multimodal interfaces have been developed and tested in a wide range of application domains. They have been shown to be effective for improving timesharing and attention management. Several studies confirm that people are capable of performing two tasks at once when the stimuli associated with those tasks are presented in different sensory channels. However, only limited anecdotal data exist on task performance when a third concurrent signal in a different modality is introduced. Also, there is no empirical data on how well senior citizens, 65 years and older, can cope with and benefit from multimodal displays. Chapters 3-5 examined these questions, both in the presence and absence of an on-going simulated driving task for three different age groups. The findings from these studies highlight breakdowns in multimodal processing when participants were presented with pairs of signals and, even more so, with multimodal triplets. The goal of this study was to test the effectiveness of one particular countermeasure – timing adjustments – to processing limitations identified in the previous experiments.

Employing a 500-millisecond time delay was found to be effective in increasing the hit rate for bi- and trimodal cues. The percentage of correct responses increased from 90.8% to 96.7%, which is much closer to the hit rate for younger adults in the first driving study (99%). Overall, missed signals decreased by 66%, while the percentage of false alarms was reduced by 44%. In particular, the reporting of only V when presented with A–V and T–V reduced by 77% and 71%, respectively. Likewise, false reports of V when presented with T–A reduced by 66%. Finally, omissions of T in the TA–V condition were cut by about one half. These findings confirm that introducing even a very short (< 1 second) interval between the presentation of two signals can significantly lessen, though not eliminate, perceptual and attentional breakdowns.

The following provides explanations for the improvement in detection performance. First, introducing spacing between two or more concurrent signals mitigated masking effects observed in previous studies. This avoided that any signal covered (or was covered by) the other stimuli (Craig & Evans, 1987 & Soto-Faraco et al., 2002). In addition, the particular timing delay of 500 msec provided participants with additional time to process each signal, and reduced the possibility for crossmodal attentional blink. Finally, visual dominance was overcome by presenting the light in the last position for all modality combinations that consisted of a visual signal. In this case, participants were presented with, and thus should have noticed, tactile or auditory stimuli first.

The percentage make-up of errors for each cue combination (with respect to the overall miss rate) did not remain the same between the two experiments (see Table 6.3). Bimodal combinations experienced decreases in the percentage of errors error, while the trimodal cue witnessed an increase.

Table 6.3: Percentage change in make-up of errors comparison for bi- and tri-modal cues between the concurrent and offset signal timing conditions

Modality combination	Concurrent signal	Offset signal	% change
VA	16.7%	10.3%	6.4% (decrease)
VT	15.7%	12.8%	2.9% (decrease)
AT	13.9%	12.8%	1.1% (decrease)
VAT	19.4%	23.0%	3.6% (increase)

Even though the total number of incorrect responses was reduced across all combinations, the percentages in the table imply that some perceptual and attentional limitations may still persist – since no value of the offset task was 0%. One possible explanation for this finding surfaced during the debriefing sessions with participants. Although participants collectively agreed that delaying one signal helped them with the detection task, they also reported that, subjectively, the cues still appeared to them as one combined signal. This suggests that overcoming these problems may require a combination of countermeasures, as opposed to one alteration alone (Hameed & Sarter, 2009). For example, it may be necessary to employ salience adjustments to missed signals (i.e., increasing the intensity of one or more signals to make it appear more conspicuous than the others).

Contrary to our expectations, none of the driving measures were significantly affected by introducing SOAs between two signals. There were trends towards poorer performance, for lane position and lateral velocity, which might have been the result of increased mental demands. The timing delay afforded participants more time to process and correctly assign each cue. However, it is likely that the small sample size used in this experiment did not have the power to produce significant results.

In conclusion, this study confirmed that separating signals by even a small amount of time could significantly increase the likelihood that signals are detected. This may be accomplished by avoiding attentional blink, sensory dominance, and other masking phenomena. These adjustments are assumed to benefit primarily older adults who experience difficulties with divided attention. The work presented here represents a first step towards the ultimate goal of developing adaptive displays that can overcome limitations associated with using multimodal displays in data-rich environments, for any age group, but especially for older adults.

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CHAPTER 7

Conclusion

Most human-machine interfaces still rely primarily on the visual channel for presenting information to operators. This tendency, in combination with the introduction of more and increasingly complex technologies and associated tasks and interfaces, has resulted in visual data overload and associated performance breakdowns in many work environments. In recent years, multimodal displays, i.e., displays that distribute information across vision, audition, and touch, have been explored and shown to be a promising means of addressing these challenges (Ho, Tan, & Spence, 2005; Sarter, 2006; Spence & Driver, 1997; Wickens, 2008).

However, as mentioned earlier, almost all studies on the effectiveness of multimodality to date have examined the concurrent processing of only two stimuli in different sensory channels (in most cases, vision and hearing). Very limited and mostly anecdotal evidence exists on task and detection performance when a third signal in another modality is introduced. For example, the driver of a vehicle may be presented with a visual GPS notification, an auditory collision warning, and a vibrotactile blind spot indication – all at the same time. One of the few empirical studies examining detection performance for multimodal triplets (Hecht & Reiner, 2009) showed that, presumably due to sensory dominance effects, participants failed to notice one or more signals when presented with three simultaneous unrelated stimuli.

In addition to a lack of empirical data regarding the processing of three or more concurrent signals, the effects of aging on multimodal information processing is ill-understood. A rapidly growing segment of the population – adults 65 years and older – is known to suffer from varying declines in sensory abilities (e.g., Li & Lindenberger, 2002; Stuart-Hamilton, 2012) and also generally experience difficulty with divided attention (e.g., McDowd & Craik, 1988; Somberg & Salthouse, 1982). It is not clear how well these older adults can cope with, and whether they will benefit from multimodal displays which they are likely to encounter in modern car cockpits, for example.

The goals of this dissertation were to fill the above gaps in the literature on the processing and presentation of multimodal information. Before studies could be conducted to answer the above questions, there was a need to first develop a more valid and reliable method for enabling people to subjectively adjust/equate the intensity of stimuli across sensory channels. This process is referred to as 'crossmodal matching,' and represents an important first step for avoiding that modality is confounded with other properties, most notably, signal salience. To date, this step has been neglected by the vast majority of multimodal research.

Once the crossmodal matching technique had been developed, two experiments were conducted to (1) establish the extent to which younger and older adults can detect and process non-redundant cues that appear concurrently in vision, hearing, and/or touch and (2) examine this ability both in isolation and while performing a concurrent task (driving) in parallel. Finally, in the last experiment, the timing of cues was adjusted to try and overcome observed performance decrements, especially in older retired participants.

Chapter 2 describes how the first goal in this line of research – to develop a reliable and efficient crossmodal matching technique – was achieved. Three different crossmodal matching techniques for the same visual-auditory, visual-tactile, and auditory-tactile pairs were compared to one-another to determine whether they resulted in comparable and acceptable levels of within-subject variability. The three techniques varied with respect to the controls used to adjust stimulus intensity and the associated feedback about the match values. The findings from this first phase of my research not only confirm the need for crossmodal matching (due to the high between-subject variability observed; e.g., Marks, 1988; Gescheider, 1988; Stevens, 1959) but also highlight that performing a single and unidirectional match between two modalities is not sufficient to account for high intra-individual variability. In addition, the specific implementation of the matching task was found to affect within-subject variability. The keyboard arrows design, which afforded more incremental adjustments and did not provide visual feedback, led to the most consistent matching across trials. As a result, it was employed in the remaining phases of this work.

Chapters 3-5 describe the two experiments that were conducted to investigate how well younger and older adults can process non-redundant cues that appear concurrently in two or three sensory modalities. In experiment 1 (chapter 3), age and cue modality/cue combinations were varied in the absence of an on-going visual/manual task. Findings revealed that older adults, regardless of whether employed or retired, responded significantly slower to all cue combinations, compared to younger adults (Laurienti et al., 2006; Mahoney et al., 2012). Also, as expected, accuracy for older retired adults was lower than that of younger and older working participants. Experiment 2 (chapter 4) sought to answer the same question, but did so in the context of a simulated driving task – the application domain for this research. Response times to all cues were significantly delayed in the driving (dual task) condition, compared to single task alone. This was likely a result of increased workload and task interference. Surprisingly, however, hit rate was not affected by task condition. The relatively low attentional demands associated with the driving scenario may explain this finding. Deviations in lane position and lateral velocity were significantly greater for both older adult groups, and the trimodal visual-auditory-tactile (VAT) signal caused the greatest deviations in speed for everyone.

Another interesting finding is that the pattern of breakdowns in signal detection differed between younger and older participants, but was similar for the two groups of older adults who accounted for the largest percentage of errors. They repeatedly failed to notice the tactile signal when it was combined with visual **and** auditory signals. They also had a tendency to report only the visual cue when presented with auditory **or** tactile cues, and often falsely reported a visual signal in combination with an auditory **and** tactile cue. These findings warrant the development of countermeasures in the form of adaptive displays that can overcome perceptual limitations.

To this end, a third experiment was conducted which was described in chapter 6. Here, a 500-millisecond SOA/delay was introduced to all bi- and trimodal cues, based on previous research and empirical data on minimum response times. Also, the visual stimulus was always presented last, and the tactile cue first, to reduce the risk of a visual dominance and masking effects, respectively. Overall, these adjustments of timing and position were found to be effective at increasing hit rates for bi- and trimodal cue combinations (though accuracy was still not 100%). Response times and driving performance were not affected by the adaptive design.

Overall, this work represents critical first steps in both establishing and counteracting limits of multisensory information processing. It also suggests that proper context-sensitive design can be used to reduce the performance gap between younger and older people and thus support the ‘aging-in-place’ research initiative (Dishman, 2004; Mynatt, Essa, & Rogers, 2000; Mynatt et al., 2004).

Intellectual Merit and Broader Impact

The work presented in this dissertation adds to the knowledge base, and contributes to advancing and expanding theories and frameworks in multimodal information processing and display design. It also makes an important contribution to the development of research methods in this field of study.

First, a more reliable, and relatively easy to use, technique for performing crossmodal matching was developed, which can be used by other laboratories in future multimodal studies to avoid confounding modality with other signal properties. Secondly, the controlled experiments pointed to possible shortcomings of multimodal information processing, both in isolation and when combined with an on-going concurrent task. They also confirmed that effects were more prevalent in older adults, suggesting the need for more research to better understand age-related capabilities and limitations, as well as aging- and generation-oriented approaches for explaining their behavior (Liu & Joines, 2012). Finally, a promising countermeasure for overcoming limits in the ability to process simultaneous, non-redundant information in multiple sensory channels was proposed and tested. Findings from this research can also be used to inform the further development of qualitative and quantitative models of human perception and information processing, such as N-SEEV and MRT (Steelman-Allen et al. 2009; Wickens 2003, 2008, 2009), as well as agent-based computations of human performance, such as QN-MHP (e.g., Liu, Feyen, & Tsimhoni, 2006).

From an applied perspective, the work will contribute to improved safety in the automotive domain. Modern car cockpits are becoming increasingly data-rich, and information is being presented to drivers in visual, auditory, and recently also tactile form. This increases the chance for two or more signals to appear in tandem. At the same time, there will be a surge in the number of drivers 65 years and older who – as highlighted by this work – are more likely to miss combinations of signals. It is therefore critical that car interface designers understand and take into account known age-associated perceptual and cognitive limitations. In terms of application of findings, one possibility is to implement multimodal displays in such a way that operators can select their own preferred settings for various signal parameters (e.g., signal salience, duration) the first time they use the display. These values could then be stored and activated every time the driver gets into the vehicle. If employed, this method would have to be designed to ensure that performance and safety are not jeopardized at the expense of user preference (Andre and Wickens, 1995). An alternative approach would be the use of a hybrid display – which combines functions of both adaptable and adaptive displays. This scheme allows the human and system to work together and would counterbalance the benefits and disadvantages of each type of display in isolation.

Safeguarding operators against missing important information altogether represents a major first step towards improving operator and public safety. Ultimately, the findings from this research are expected to generalize to other high-risk domains and inform multimodal display design in a range of high-risk, data-rich, and complex environments (e.g., aviation, space, military, and medicine).

Future Work

The work reported in this dissertation represents a significant contribution to the understanding of multimodal information processing and display design. However, as with any research initiative, it also raises a host of new, unanswered questions and suggests several future research thrusts. I plan to address these issues as part of the research agenda I establish as an

Assistant Professor in the School of Industrial Engineering at Purdue University starting January 2017.

First, this research investigated the ability to process non-redundant trimodal cues, both in isolation and in parallel with a concurrent task. The second (driving) experiment provided baseline performance data for the detection and driving tasks in the absence of stimuli that could distract or interfere with noticing signals. As a result, it was not quite representative of the real challenges faced by drivers on a daily basis. The next step would therefore be to include more realistic highway components, such as surrounding traffic, additional road scenery, sounds, and vibrations, to increase workload and divided attention demands.

Similarly, the multimodal signals used in this experiment did not have any associated meanings, and thus inherent priorities, which may affect response times, hit rates, and driving performance. This may be especially true if each cue requires a separate response. Manipulating this variable (task relevance and semantics) may result in different strategies employed by participants. It may also inform modality mappings by matching type of information to the most appropriate sensory channel (e.g., presenting spatial information using the tactile modality; Lu et al., 2013).

With respect to aging-related research initiatives, Liu & Joines (2012) suggest that interface design for older adults can be guided by a framework that considers both aging- and generation-oriented perspectives (see Figure 7.1). The aging-oriented approach provides an understanding of user characteristics by focusing on changes in age-related abilities (such as perceptual and attentional declines) during the aging process – i.e., their limitations. The latter case, the generation-oriented approach, considers the knowledge and experiences gained through generation-specific interactions with the world, such as affordances and expectations of certain technologies – i.e., their capabilities.

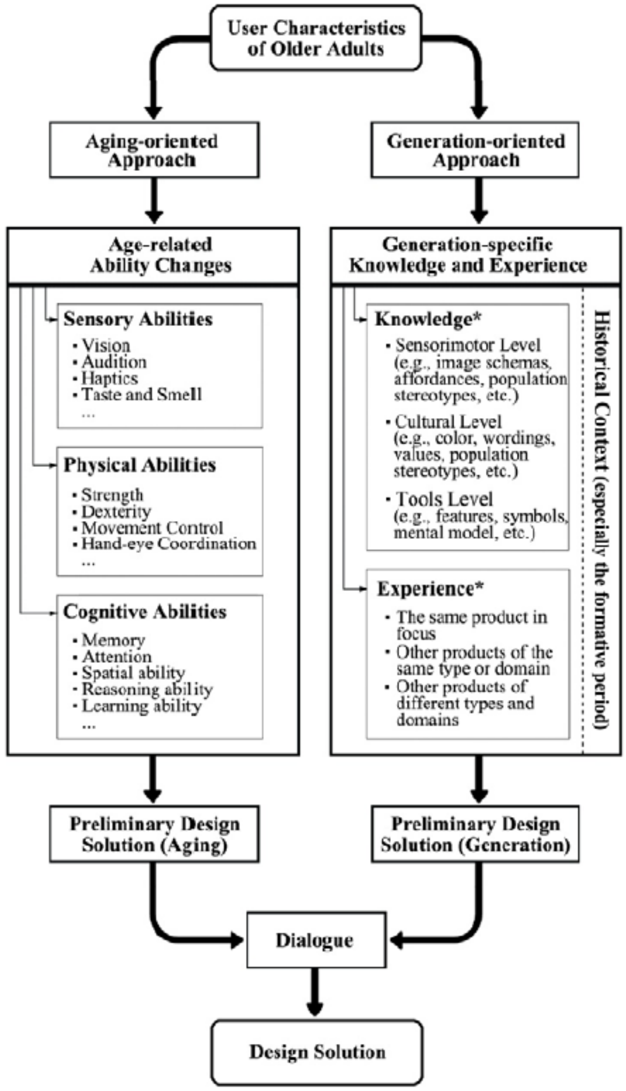

Figure 7.1: A framework of guiding interface design for older adults (adopted from Liu & Joines, 2012)

A third research interest is the development of adaptive multimodal displays to support divided attention in older adults. As previewed in the Introduction of this dissertation, and as highlighted by the findings of this work, older adults may perform better when their attention is focused mainly on one task. Adaptive displays can adjust the amount, timing, and location of information by monitoring the driver's attentional state (by means of physiological measures, for example) and performance to adjust signal parameters automatically. One question that warrants further investigation is whether eye tracking, used to trace attention allocation and information search in real-time, can be used to trigger display adjustments and support multitasking, for a wide variety of tasks, in older adults.

Finally, numerous studies have quantified negative effects of aging on driving performance, such as delayed response times, slower driving speeds, and poor maneuvering. However, very little attention has been paid to the needs and opinions of older adults, especially with respect to the perception of their own driving abilities and limitations, and tools that may be particularly beneficial to this age group. Questionnaires, interviews, and focus groups are tools that can be used to gain better insights into their driving experiences. These can, in turn, help to identify candidate preventive measures (such as adaptive windshield lighting) that are suitable and well-received by them, and that can be tested in simulated studies.

Overall, the efforts described in this dissertation are a part of a larger effort – to ensure the safety of operators in joint human-machine systems. Any contribution to this goal will contribute to a reduction in accidents and fatalities in high-risks transportation systems, in addition to costs associated with them.

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APPENDIX

1A: Participant Biographical Data Forms

Assessing the effects of aging on multimodal information processing
Participant Biographical Data Form (Experiment 1: *Single-task condition)*

Age: ______________ Sex: ____________________ Participant #: ___________

Occupation: _______________________
(If retired, please specify occupation when working, the number of years worked, and the number of years retired) ____

____

<u>Regular activities:</u>

1. Please describe any activities for which you are involved in on a regular basis, such as volunteer work/community service, physical activity, etc.

____

____

2. Do you play video or computer games often? If so, please explain them and their objectives:

____

____

3. On a scale from 1 to 5 (5 being the best; 1 being the worst), please rate how well you consider your ability to attend to multiple cues or signals at once? (For example, watching a motion picture and listening to music that might be unrelated)

|---------------|---------------|---------------|---------------|

1 2 3 4 5

4. Please explain your response below (in as much detail as possible):

____

____

____

Assessing the effects of aging on multimodal information processing
Participant Biographical Data Form (Experiment 2: *Dual-task condition)*

Participant #: ___________

Background:

Marital status:
- o Married
- o Single
- o No longer married
- o Widow/widower

If married (or were married), please indicate the number of years: ________________________________

Which is your dominant hand?
- o Left
- o Right

Driving experiences:

1. Do you have a valid driver's license?
   - o Left
   - o Right

2. On average, how many miles do you drive a week (on average)? ______________________________

3. How many years have you been driving? ____

4. What perceptual and/or cognitive changes, if any, have you noticed in yourself over the years? (In your response, please mention any issues that relate to driving)

____

____

____

____

4a. If you responded to question #4, what do you do to help you cope with/overcome these changes?

____

____

____

5. Does your current vehicle contain info/entertainment systems? (For example, alerting and warning systems such as lane departure warning, blind-spot notification, collision warning, etc.; weather and traffic updates, playlists, etc. – in your response, please indicate the types and modality of information presented, the frequency of alerts, how often do you use them, can they be powered off and if so, do you turn them off, etc.)

6. Do you use any assistive devices to help you perform daily tasks? (Such as, home automation systems, assistive home robots or specialized watches/laptops)

7. After having completed the previous experiment (single-task condition), on a scale from 1 to 5 (5 being the best; 1 being the worst), please rate how well you consider your ability to attend to multiple cues or signals at once?

|---------------|---------------|---------------|---------------|

1 2 3 4 5

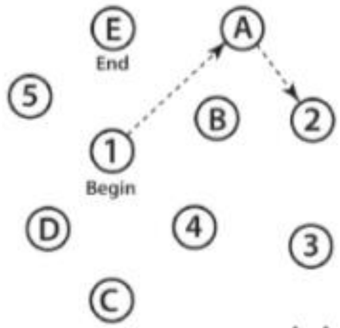
Please explain your response below (in as much detail as possible):

1B: Montreal Cognitive Assessment (MoCA)

MONTREAL COGNITIVE ASSESSMENT (MOCA)
Version 7.1 Original Version

NAME :
Education :
Sex :
Date of birth :
DATE :

VISUOSPATIAL / EXECUTIVE — POINTS



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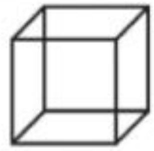


Copy cube

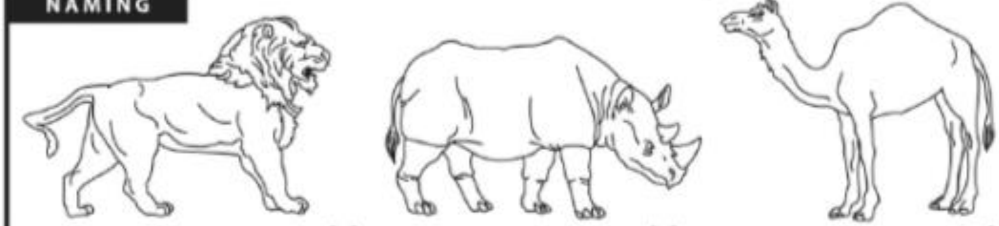
[ ]

Draw CLOCK (Ten past eleven)
(3 points)

[ ] Contour [ ] Numbers [ ] Hands

___/5

NAMING



[ ] [ ] [ ]

___/3

MEMORY Read list of words, subject must repeat them. Do 2 trials, even if 1st trial is successful. Do a recall after 5 minutes.

	FACE	VELVET	CHURCH	DAISY	RED
1st trial					
2nd trial					

No points

ATTENTION Read list of digits (1 digit/ sec.).

Subject has to repeat them in the forward order [ ] 2 1 8 5 4
Subject has to repeat them in the backward order [ ] 7 4 2

___/2

Read list of letters. The subject must tap with his hand at each letter A. No points if ≥ 2 errors

[ ] FBACMNAAJKLBAFAKDEAAAJAMOFAAB

___/1

Serial 7 subtraction starting at 100 [ ] 93 [ ] 86 [ ] 79 [ ] 72 [ ] 65

4 or 5 correct subtractions: **3 pts**, 2 or 3 correct: **2 pts**, 1 correct: **1 pt**, 0 correct: **0 pt**

___/3

LANGUAGE Repeat : I only know that John is the one to help today. [ ]
The cat always hid under the couch when dogs were in the room. [ ]

___/2

Fluency / Name maximum number of words in one minute that begin with the letter F [ ] ____ (N ≥ 11 words)

___/1

ABSTRACTION Similarity between e.g. banana - orange = fruit [ ] train – bicycle [ ] watch - ruler

___/2

DELAYED RECALL	Has to recall words	FACE	VELVET	CHURCH	DAISY	RED	Points for UNCUED recall only
	WITH NO CUE	[ ]	[ ]	[ ]	[ ]	[ ]	
Optional	Category cue						
	Multiple choice cue						

___/5

ORIENTATION [ ] Date [ ] Month [ ] Year [ ] Day [ ] Place [ ] City

___/6

© Z.Nasreddine MD **www.mocatest.org** Normal ≥ 26 / 30 TOTAL ___/30

Administered by: ____________________

Add 1 point if ≤ 12 yr edu

Montreal Cognitive Assessment (MoCA)

Nasreddine Z.

Nasreddine, Z. S., Phillips, N. A., Bedirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., and Chertkow, H. 2005. "The Montreal Cognitive Assessment, MoCA: a Brief Screening Tool for Mild Cognitive Impairment." *J.Am.Geriatr.Soc.* 53(4):695-99.

Administration and Scoring Instructions

Time to administer the MoCA is approximately 10 minutes. The total possible score is 30 points; a score of 26 or above is considered normal.

1. Alternating Trail Making:
Administration: The examiner instructs the subject: "Please draw a line, going from a number to a letter in ascending order. Begin here [point to (1)] and draw a line from 1 then to A then to 2 and so on. End here [point to (E)]."
Scoring: Allocate one point if the subject successfully draws the following pattern: 1 −A- 2- B- 3- C- 4- D- 5- E, without drawing any lines that cross. Any error that is not immediately self-corrected earns a score of 0.

2. Visuoconstructional Skills (Cube):
Administration: The examiner gives the following instructions, pointing to the **cube**: "Copy this drawing as accurately as you can, in the space below".
Scoring: One point is allocated for a correctly executed drawing.

- Drawing must be three-dimensional
- All lines are drawn
- No line is added
- Lines are relatively parallel and their length is similar (rectangular prisms are accepted)

A point is not assigned if any of the above-criteria are not met.

3. Visuoconstructional Skills (Clock):
Administration: Indicate the right third of the space and give the following instructions: "Draw a **clock**. Put in all the numbers and set the time to 10 after 11".
Scoring: One point is allocated for each of the following three criteria:

- ☐ Contour (1 pt.): the clock face must be a circle with only minor distortion acceptable (e.g., slight imperfection on closing the circle);
- ☐ Numbers (1 pt.): all clock numbers must be present with no additional numbers; numbers must be in the correct order and placed in the approximate quadrants on the clock face; Roman numerals are acceptable; numbers can be placed outside the circle contour;
- ☐ Hands (1 pt.): there must be two hands jointly indicating the correct time; the hour hand must be clearly shorter than the

minute hand; hands must be centred within the clock face with their junction close to the clock centre.

A point is not assigned for a given element if any of the above-criteria are not met.

4. Naming:
Administration: Beginning on the left, point to each figure and say: "Tell me the name of this animal".
Scoring: One point each is given for the following responses: (1) camel or dromedary, (2) lion, (3) rhinoceros or rhino.

5. Memory:
Administration: The examiner reads a list of 5 words at a rate of one per second, giving the following instructions: "This is a memory test. I am going to read a list of words that you will have to remember now and later on. Listen carefully. When I am through, tell me as many words as you can remember. It doesn't matter in what order you say them". Mark a check in the allocated space for each word the subject produces on this first trial. When the subject indicates that (s)he has finished (has recalled all words), or can recall no more words, read the list a second time with the following instructions: "I am going to read the same list for a second time. Try to remember and tell me as many words as you can, including words you said the first time." Put a check in the allocated space for each word the subject recalls after the second trial.
At the end of the second trial, inform the subject that (s)he will be asked to recall these words again by saying, "I will ask you to recall those words again at the end of the test."
Scoring: No points are given for Trials One and Two.

6. Attention:
Forward Digit Span: Administration: Give the following instruction: "I am going to say some numbers and when I am through, repeat them to me exactly as I said them". Read the five number sequence at a rate of one digit per second.
Backward Digit Span: Administration: Give the following instruction: "Now I am going to say some more numbers, but when I am through you must repeat them to me in the backwards order." Read the three number sequence at a rate of one digit per second.
Scoring: Allocate one point for each sequence correctly repeated, (N.B.: the correct response for the backwards trial is 2-4-7).
Vigilance: Administration: The examiner reads the list of letters at a rate of one per second, after giving the following instruction: "I am going to read a sequence of letters. Every time I say the letter A, tap your hand once. If I say a different letter, do not tap your hand".
Scoring: Give one point if there is zero to one errors (an error is a tap on a wrong letter or a failure to tap on letter A).
Serial 7s: Administration: The examiner gives the following instruction: "Now, I will ask you to count by subtracting seven from 100, and then, keep subtracting seven from your answer until I tell you to stop." Give this instruction twice if necessary.
Scoring: This item is scored out of 3 points. Give no (0) points for no correct subtractions, 1 point for one correction subtraction, 2 points for two-to-three correct subtractions, and 3 points if the participant successfully makes four or five correct

subtractions. Count each correct subtraction of 7 beginning at 100. Each subtraction is evaluated independently; that is, if the participant responds with an incorrect number but continues to correctly subtract 7 from it, give a point for each correct subtraction. For example, a participant may respond "92 – 85 – 78 – 71 – 64" where the "92" is incorrect, but all subsequent numbers are subtracted correctly. This is one error and the item would be given a score of

7. Sentence repetition:

Administration: The examiner gives the following instructions: "I am going to read you a sentence. Repeat it after me, exactly as I say it [pause]: **I only know that John is the one to help today.**" Following the response, say: "Now I am going to read you another sentence. Repeat it after me, exactly as I say it [pause]: **The cat always hid under the couch when dogs were in the room.**"

Scoring: Allocate 1 point for each sentence correctly repeated. Repetition must be exact. Be alert for errors that are omissions (e.g., omitting "only", "always") and substitutions/additions (e.g., "John is the one who helped today;" substituting "hides" for "hid", altering plurals, etc.).

8. Verbal fluency:

Administration: The examiner gives the following instruction: "Tell me as many words as you can think of that begin with a certain letter of the alphabet that I will tell you in a moment. You can say any kind of word you want, except for proper nouns (like Bob or Boston), numbers, or words that begin with the same sound but have a different suffix, for example, love, lover, loving. I will tell you to stop after one minute. Are you ready? [Pause] Now, tell me as many words as you can think of that begin with the letter F. [time for 60 sec]. Stop."

Scoring: Allocate one point if the subject generates 11 words or more in 60 sec. Record the subject's response in the bottom or side margins.

9. Abstraction:

Administration: The examiner asks the subject to explain what each pair of words has in common, starting with the example: "Tell me how an orange and a banana are alike". If the subject answers in a concrete manner, then say only one additional time: "Tell me another way in which those items are alike". If the subject does not give the appropriate response (fruit), say, "Yes, and they are also both fruit." Do not give any additional instructions or clarification.

After the practice trial, say: "Now, tell me how a train and a bicycle are alike". Following the response, administer the second trial, saying: "Now tell me how a ruler and a watch are alike". Do not give any additional instructions or prompts.

Scoring: Only the last two item pairs are scored. Give 1 point to each item pair correctly answered. The following responses are acceptable:

Train-bicycle = means of transportation, means of travelling, you take trips in both;

Ruler-watch = measuring instruments, used to measure.

The following responses are **not** acceptable: Train-bicycle = they have wheels; Ruler-watch = they have numbers.

10. Delayed recall:

Administration: The examiner gives the following instruction: "I read some words to you earlier, which I asked you to remember. Tell me as many of those words as you can remember. Make a check mark (□) for each of the words correctly recalled spontaneously without any cues, in the allocated space.

Scoring: **Allocate 1 point for each word recalled freely without any cues**.

Optional:

Following the delayed free recall trial, prompt the subject with the semantic category cue provided below for any word not recalled. Make a check mark (□) in the allocated space if the subject remembered the word with the help of a category or multiple-choice cue. Prompt all non-recalled words in this manner. If the subject does not recall the word after the category cue, give him/her a multiple choice trial, using the following example instruction, "Which of the following words do you think it was, NOSE, FACE, or HAND?"

Use the following category and/or multiple-choice cues for each word, when appropriate:

FACE: category cue: part of the body multiple choice: nose, face, hand
VELVET: category cue: type of fabric multiple choice: denim, cotton, velvet
CHURCH: category cue: type of building multiple choice: church, school, hospital
DAISY: category cue: type of flower multiple choice: rose, daisy, tulip
RED: category cue: a colour multiple choice: red, blue, green

Scoring: **No points are allocated for words recalled with a cue.** A cue is used for clinical information purposes only and can give the test interpreter additional information about the type of memory disorder. For memory deficits due to retrieval failures, performance can be improved with a cue. For memory deficits due to encoding failures, performance does not improve with a cue.

11. Orientation:

Administration: The examiner gives the following instructions: "Tell me the date today". If the subject does not give a complete answer, then prompt accordingly by saying: "Tell me the [year, month, exact date, and day of the week]." Then say: "Now, tell me the name of this place, and which city it is in."

Scoring: Give one point for each item correctly answered. The subject must tell the exact date and the exact place (name of hospital, clinic, office). No points are allocated if subject makes an error of one day for the day and date.

TOTAL SCORE: Sum all subscores listed on the right-hand side. Add one point for an individual who has 12 years or fewer of formal education, for a possible maximum of 30 points. A final total score of 26 and above is considered normal.

1C: Participant Debriefing Forms

Assessing the effects of aging on multimodal information processing

Debriefing Questionnaire (Experiment 1: *Single-task condition)*

Participant #: ________________________

1. On a scale from 1 to 10 (10 being the most difficult; 1 being the easiest), please rate the ease of performing the crossmodal matching task (e.g., the task that involved adjusting and equating the intensity of the visual, auditory, and tactile stimuli to match one-another):

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

Please provide any comments regarding matching the intensity of the cues to one-another:

____

____

____

____

2. On a scale from 1 to 10 (10 being the most difficult; 1 being the easiest), please rate the ease of detecting each cue/cue combination (V = visual, A = auditory, T = tactile):

1 2 3 4 5 6 7 8 9 10

V alone |--------|--------|--------|--------|--------|--------|--------|--------|--------|

A alone |--------|--------|--------|--------|--------|--------|--------|--------|--------|

T alone |--------|--------|--------|--------|--------|--------|--------|--------|--------|

V combined with A |--------|--------|--------|--------|--------|--------|--------|--------|--------|

V combined with T |--------|--------|--------|--------|--------|--------|--------|--------|--------|

A combined with T |--------|--------|--------|--------|--------|--------|--------|--------|--------|

V combined with A and T |--------|--------|--------|--------|--------|--------|--------|--------|--------|

3. Did you find any cue(s) (visual, auditory, tactile, or any of the combinations) more difficult (or easier) to detect compared to others? Please explain ____

____

____

____

____

4. Did you use any strategies to help you anticipate and/or detect the cues? _______________________

____

____

____

5. Please comment on length of the detection task (e.g., is this something you would be able to do for several hours on multiple days) ____

____

____

____

6. Please comment on your level of comfort while performing the detection task ___________________

____

____

7. Any other observations, problems, or general comments are appreciated

____

____

____

8. Please indicate if you would like to participate in future experiments (if so, please provide your email address) ____

____

Assessing the effects of aging on multimodal information processing

Debriefing Questionnaire (Experiment 2: *Dual-task condition)*

Participant #: ________________________

1. Compared to experiment 1, on a scale from 1 to 10 (10 being the most difficult; 1 being the easiest), please rate the ease of performing the crossmodal matching task:

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

Please provide any comments regarding matching the intensity of the cues to one-another:

____

____

____

2. On a scale from 1 to 10 (10 being the most difficult; 1 being the easiest), please rate the ease of detecting each cue/cue combination (V = visual, A = auditory, T = tactile):

	1	2	3	4	5	6	7	8	9	10
V alone										
A alone										
T alone										
V combined with A										
V combined with T										
A combined with T										
V combined with A and T										

3. Did you find any cue(s) (visual, auditory, tactile, or any of the combinations) more difficult (or easier) to detect compared to others? Please explain. ____

____

____

____

4. On a scale from 1 to 10 (10 being the best; 1 being the worst), please rate your ability to detect cues and maintain proper vehicle control (e.g., lane keeping, obeying speed limit, etc.) simultaneously:

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

5. Do you feel that you were more focused on steering the vehicle properly, or anticipating/detecting the next cue? Please explain as much as possible. ____

____

____

____

5a. Did you use any strategies to help you detect the cues? ____________________________________

____

____

____

6. Did you use any strategies to help you driven the vehicle and detect the cues, or to achieve an even balance between both? ____

____

____

7. Compared to experiment 1, on a scale from 1 to 10 (10 being the highest; 1 being the lowest), how would you rate the overall workload of driving the vehicle and anticipating/detecting the events?

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

8. Please comment on length of the task: ____

____

____

9. Please comment on your level of comfort while performing the detection task: _________________

____

____

10. Any other observations, problems, or general comments are appreciated:

____

____

____

11. Please indicate if you would like to participate in future experiments: _______________________

____

Assessing the effects of aging on multimodal information processing
Debriefing Questionnaire (Experiment 3: *Timing adjustments)*

Participant #: ________________________

1. On a scale from 1 to 10 (10 being the most difficult; 1 being the easiest), please rate the ease of detecting each cue/cue combination (V = visual, A = auditory, T = tactile):

	1	2	3	4	5	6	7	8	9	10
V alone	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
A alone	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
T alone	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
V combined with A	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
V combined with T	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
A combined with T	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	
V combined with A and T	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------	|--------|	

2. Did you find any cue(s) (visual, auditory, tactile, or any of the combinations) more difficult (or easier) to detect compared to others? Please explain. ____

____

____

____

____

3. On a scale from 1 to 10 (10 being the best; 1 being the worst), please rate your ability to detect cues and maintain proper vehicle control (e.g., lane keeping, obeying speed limit, etc.) simultaneously:

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

4. Do you feel that you were more focused on steering the vehicle properly, or anticipating/detecting the next cue? Please explain as much as possible. ____

____

____

____

5. Did you use any strategies to help you detect the cues? ___________________________________

____

____

____

6. Did you use any strategies to help you driven the vehicle and detect the cues, or to achieve an even balance between both? ____

____

____

7. Compared to the previous driving experiment, on a scale from 1 to 10 (10 being the highest; 1 being the lowest), how would you rate the overall workload of driving the vehicle and anticipating/detecting the events?

1 2 3 4 5 6 7 8 9 10

|--------|--------|--------|--------|--------|--------|--------|--------|--------|

8. Any other observations, problems, or general comments are appreciated:

____

____

____