What You Don't Notice Can Harm You: Age-Related Differences in Detecting Concurrent Visual, Auditory, and Tactile Cues

Brandon J. Pitts, Purdue University, West Lafayette, Indiana, and
Nadine Sarter, University of Michigan, Ann Arbor

Objective: This research sought to determine whether people can perceive and process three nonredundant (and unrelated) signals in vision, hearing, and touch at the same time and how aging and concurrent task demands affect this ability.

Background: Multimodal displays have been shown to improve multitasking and attention management; however, their potential limitations are not well understood. The majority of studies on multimodal information presentation have focused on the processing of only two concurrent and, most often, redundant cues by younger participants.

Method: Two experiments were conducted in which younger and older adults detected and responded to a series of singles, pairs, and triplets of visual, auditory, and tactile cues in the absence (Experiment 1) and presence (Experiment 2) of an ongoing simulated driving task. Detection rates, response times, and driving task performance were measured.

Results: Compared to younger participants, older adults showed longer response times and higher error rates in response to cues/cue combinations. Older participants often missed the tactile cue when three cues were combined. They sometimes falsely reported the presence of a visual cue when presented with a pair of auditory and tactile signals. Driving performance suffered most in the presence of cue triplets.

Conclusion: People are more likely to miss information if more than two concurrent nonredundant signals are presented to different sensory channels.

Application: The findings from this work help inform the design of multimodal displays and ensure their usefulness across different age groups and in various application domains.

Keywords: multimodal information processing, trimodal cueing, concurrent signals, aging, driving

Address correspondence to Brandon J. Pitts, School of Industrial Engineering, Purdue University, 315 N. Grant Street, West Lafayette, IN 47907-2023, USA; e-mail: bjpitts@purdue.edu.

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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 may be alerted by an auditory signal warning that a leading vehicle has suddenly applied brakes, and a vibration to the steering wheel may indicate that the vehicle is drifting out of the lane. In this particular situation, the driver receives, simultaneously, information about three different events in three sensory modalities (vision, hearing, and touch) and needs to notice, interpret, and respond quickly and appropriately to each of them.

To support operator performance in such data-rich domains, multimodal displays, which present information via multiple sensory channels, have been introduced as a promising means of improving multitasking and attention management (e.g., Calvert, Spence, & Stein, 2004; Giang et al., 2010; Sarter, 2002, 2006, 2007; Spence & Driver, 1997a; Wickens, 2008). However, the limitations of multimodal information processing 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, namely, cues that provided the same information or referred to the same event (e.g., Hecht, Reiner, & Halevy, 2006; Lees et al., 2012; Murata, Kanbayashi, & Hayami, 2013). These studies have found that in general, response times to combined cues (both pairs and triplets, referred to as bi- and trimodal, respectively) are shorter than to single

stimuli, with no significant difference between bi- and trimodal cues. For example, in a generic detection task, Hecht et al. (2006) presented participants with redundant pairs and triplets of visual, auditory, and haptic (force) cues. Response times to trimodal cues were shorter than for bimodal, which were responded to quicker than unimodal cues. In a different study (Politis, Brewster, & Pollick, 2014), drivers were presented with warnings about braking events from a lead vehicle, which appeared as singles, doubles, and triplets of visual, auditory, and tactile stimuli. Here, participants responded equally faster to all multimodal combinations compared to single stimuli without bias toward a particular signal combination.

With the redundant cues employed in the aforementioned studies, it is sufficient if at least one of the signals is noticed. In contrast, in the earlier prototypical example, the driver would need to detect and process all three signals: the driving directions, the collision warning, and the lane departure warning. Anecdotal evidence and the only empirical study (Hecht & Reiner, 2009) examining this situation suggest that a person is likely to miss one or more signals when presented with three nonredundant multimodal cues at the same time. Hecht and Reiner (2009) reported that when participants were presented with multimodal stimulus pairs and asked to respond separately to each modality signal, most errors involved noticing only the visual cues while missing the auditory or haptic signal. Using the same response method for trimodal cues, participants erred most often by responding to two rather than only one of the three cues (5.5% compared to 1.3%, respectively), without modality bias.

Another important yet unanswered question regarding the use of multimodal displays relates to the effect of aging on the ability to divide attention between multiple sensory channels. Older adult individuals often suffer from declines in sensory abilities, such as a reduction in the visual field (e.g., Stuart-Hamilton, 2012), a reduced ability to detect higher frequency sounds (e.g., He, Dubno, & Mills, 1998), and decreased sensitivity to tactile signals (e.g., Thornbury & Mistretta, 1981). They are also known to experience difficulties with divided attention, resulting in poor timesharing and delayed response times (e.g., Birren & Schaie, 2005; McDowd, Vercruyssen, & Birren, 1991; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). Still, the vast majority of studies on multimodal displays have involved younger participants only. It is therefore 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. By the year 2030, they will make up 21% of the total U.S. population (approximately 72 million people) and more than 25% of the U.S. workforce (U.S. Census Bureau, 2010). As a result, older adults will be more likely to encounter multimodal displays in workplaces and various environments (e.g., driving) that have no enforced retirement age.

The two main goals of the present study are therefore to (1) establish whether people can perceive and process more than two nonredundant cues that appear concurrently in visual, auditory, and tactile form and (2) investigate how aging and concurrent task demands modulate this multimodal information processing ability. To this end, two experiments were conducted that differed with respect to the presence of an ongoing visual-manual task: driving (absent in Experiment 1; present in Experiment 2). In this study, the cues/signals required both a single manual response (used to capture response times) and individual verbal responses. However, given that the research question was to determine the extent to which people can perceive three simultaneous but unrelated cues, we focused our analysis more heavily on the nonredundant aspects of the responses. The findings from this work will help identify limitations of multimodal information processing and may suggest countermeasures to ensure the robustness of multimodal displays.

EXPERIMENT 1

The purpose of Experiment 1 was to determine how well younger and older adults are able to detect nonredundant simultaneous cues in three different sensory channels in the absence of a concurrent task. Based on the findings of Hecht and Reiner (2009), performance (detection rate and response time) was expected to

TABLE 1: Basic Demographic Factors for Each Age Group

Factor	Younger Adults	Older Adults (Working)	Older Adults (Retired)
Mean age (*SD*)	22.67 (2.71)	68.16 (3.76)	68.33 (2.20)
Range	19–27	65–78	65–72
Mean years worked (*SD*)	—	34.06 (9.58)	34.86 (5.55)
Mean years retired (*SD*)	—	—	8.29 (4.55)
Male	8	6	5
Female	4	6	7

suffer significantly if a person is asked to notice and report three (as compared to two) simultaneous multimodal signals. We also expected that this performance decrement would be more pronounced in older participants.

Methods

Participants. Thirty-six participants volunteered to take part in this experiment. They were evenly divided into three age groups: 12 younger adults, 12 older working adults, and 12 older retired adults. Participants in the younger adult category were students at the University of Michigan (UM). Older adult participants in both groups were healthy citizens of Ann Arbor and surrounding areas recruited through the Claude D. Pepper Older Americans Independence Center control registry (managed by the UM Geriatrics Center and Institute of Gerontology) and from UM at large. Half of these individuals currently work full-time in occupations imposing considerable cognitive demands (e.g., business owner, manager, professor, etc.). The remaining half was retired from the same type of occupations and had no current employment. Older registry enrollees were prescreened by the Geriatrics Center to confirm their eligibility. All participants reported normal to corrected-to-normal vision, no significant hearing impairments, and no compromised sense of touch. Table 1 summarizes the demographic background for each age group. All participants gave informed consent and were compensated for their time in the experiment. This study was approved by the UM Health Sciences and Behavioral Sciences Institutional Review Board (ID No. HUM00099323).

Research suggests that chronological age alone may not be a good indicator of performance (e.g., Fisk, Czaja, Rogers, Charness, & Sharit, 2009; Rogers, 1997) but rather age in combination with various physical and psychological factors. Therefore, our goal in recruiting participants from both working and retired older populations was to examine whether continued cognitive demands (as a result of occupation) moderate detection performance on multimodal divided attention tasks (e.g., Williams & Kemper, 2010). Prior to the experiment, all participants were administered a cognitive impairment evaluation, the Montreal Cognitive Assessment (MoCA), as well as two divided attention assessments to ensure that they were, in principle, able to perform the required tasks (results summarized in Table 2). The MoCA detects early signs of mild cognitive impairment—the transitional state between normal aging and dementia (Nasreddine et al., 2005). A score of 26 or greater indicates normal or above normal performance. The other two assessments focused on participants' attentional capabilities. The first one, a divided attention task developed by militantplatypus.com (a gaming database), required participants to track targets that moved around randomly in all (inter)cardinal directions on a computer monitor in the presence of several visual distractors. The second divided attention assessment is part of the Cognitive Psychology Resource database developed by Xavier University of Louisiana (http://cat.xula.edu/thinker/perception/attention/divided). Here, participants were asked to perform two tasks in parallel: (1) Follow a target as it moves around the screen in a pattern that creates a shape (e.g., a star, cross, or figure eight)—without leaving an outline—and name the shape, and (2) determine whether a series of words were spelled correctly. For both assessments, participants' best score out of three attempts was recorded.

TABLE 2: Scores for Cognitive Assessments for Each Age Group

Assessment		Younger Adults	Older Adults (Working)	Older Adults (Retired)
1.	MoCA (>26) (*SD*)	28.33 (1.07)	28.27 (1.49)	27.16 (1.34)
2.	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)
3.	Shape/spelling, % (*SD*)	75.69 (3.62)	59.72 (5.01)	41.0 (6.90)

Note. Assesment 1: average Montreal Cognitive Assessment (MoCA) score. Assessment 2: total number of participants in group who could successfully track the required number of targets. Assessment 3: average weighted score for performing both tracking shape and spelling tasks.

As seen in Table 2, older participants experienced more difficulty than the younger group in performing the tracking and spelling tasks at the same time (comparatively more complex than tracking visual targets), which may be attributed in part to age-related cognitive changes. Alternatively, these cognitive assessments may closely resemble academic exercises, and therefore, time since attending formal schooling could be an influence. Although this task required divided visual attention, results were expected to infer divided multimodal attention performance.

Apparatus. Participants were seated approximately 2.5 feet in front of a single 19" computer monitor on which the experiment was conducted. The visual stimulus (**V**) was a blue light-emitting diode (LED; frequency roughly 450 Hz) located in the participant's peripheral vision, at an angle of approximately 35° (10.5 inches) below the center of the computer monitor. Participants were asked to fixate on an X located directly in the center of the monitor (i.e., 5.9 inches vertically and 7.4 inches horizontally from the top and side of monitor, respectively; Figure 1). A standard-sized table tennis ball covered the LED light to increase its size and visibility, with a luminance range of 0 to 126.77 cd/m^2. Auditory cues (**A**) were 350-Hz monotone beeps transmitted via stereo headphones, with a loudness range of 0 to 88 dB. Tactile cues (**T**) were vibrations presented at 250 Hz (Jones & Sarter, 2008) using C-2 "tactors" (commercially available piezo-buzzers inside a 1" × ½" × ¼" plastic casting; by Engineering Acoustics, Inc.). The tactile signal gain was on the range of 0 to 18 dB. Two adjacent tactors were attached to a

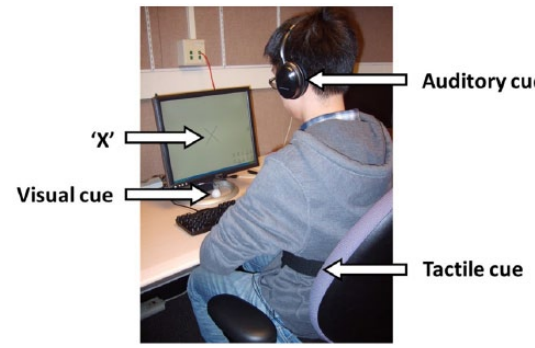

Figure 1. Experiment setup with multimodal stimulus and apparatus for Experiment 1 generic task study.

Velcro belt fastened around participants' waist and positioned on the back (posterior)/center region over clothing (i.e., Scott & Gray, 2008). Prior to the experiment, each participant was asked to perform cross-modal matching to ensure that the visual, auditory, and tactile cues were equal in terms of perceived stimulus intensity (for a complete description of the matching technique, see Pitts, Riggs, & Sarter, 2016). In summary, for this task, participants repeated a series of relative adjustments to a variable stimulus to match the intensity of a reference (or fixed) stimulus. These matches were then averaged individually for each person. At separate times during this procedure, each modality served as both the reference and variable stimulus. The off position, "zero," was the lowest possible value for each stimulus to avoid biasing minimum perceptual thresholds for each participant. Pink noise was played continuously over the stereo headphones to eliminate any audible

sounds associated with the tactor vibrations during the matching task and experiment. Overhead room lighting was turned off during this experiment.

Design. This experiment used a 3 (age group: younger, older working, and older retired) × 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.

Procedure. After signing the consent form and being informed about the purpose of the experiment, participants were asked about their daily activities, such as gaming habits, regular activities, and multitasking. Next, each participant was administered the three cognitive assessments described previously. Participants were then introduced to the full range of multimodal stimuli and asked to perform the cross-modal matching procedure. The values they selected for **V**, **A**, and **T** were used for the remainder of the experiment.

Next, participants completed a training session that emulated the actual experiment and involved the detection of 49 cues (i.e., the 7 cue/cue combinations repeated 7 times). They were required to reach a 90% accuracy level on the detection and response training tasks to proceed. For the experiment, participants were presented with 28 instances of each cue combination, resulting in a total of 196 trials per person. Each participant was exposed to the 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 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 an X located in the center of the screen to ensure that the visual cue appeared in peripheral vision. 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; each participant decided on one term for each modality and consistently used the same three terms throughout the experiment). The presentation of the subsequent signal did not depend on the preceding spacebar response. Following the experiment, participants completed a debriefing session where they were asked to comment on their experiences. The experiment lasted approximately 1 hour.

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 pressed the spacebar for that cue/cue combination, regardless of whether the verbal response was correct or not. This single response method enabled comparisons to previous work that examined redundant cues. Accuracy (% correct) was a measure of the number of cue/cue combinations the participant correctly (verbally) identified out of the total number of cue/cue combinations.

Signal detection theory (SDT) analysis was performed for each person and cue/cue combination (Macmillan & Creelman, 2005). For example, if a person was presented with a visual-auditory stimulus pair and reported **VA**, then that was recorded as a correct response ("hit"). However, if the participant reported only **V** or **A** or gave no response at all, that was classified as a missed signal ("miss"). In cases where the person reported **VT**, we labeled this a *substitution* because the tactile signal was being substituted for **A** ("miss" and "false alarm"). Finally, a **VAT** response was considered a false alarm since **T** was not part of the original modality pair ("false alarm"). Correct rejections were instances where the participant did not substitute or add a signal and did not report any signal during the time intervals when no stimulus was presented at all. 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/target

only in the presence of strong confirming evidence).

Data analysis. A mixed-model repeated measures analysis of variance (ANOVA) was used to identify main and interaction effects. In addition, two-tailed Fisher's least significant difference (LSD) post hoc tests and paired comparisons were performed to identify significant differences between means. Bonferroni corrections were applied for multiple statistical tests. Significance was set at $p < .05$, and partial eta squared (η_p^2) was used as a measure of effect size. A standard correction method was used to calculate SDT parameters—sensitivity (d') and response bias (β)—in cases where hit or false alarm rates were 0% or 100%. These values were converted to $1/(2N)$ (minimum) and $1 - 1/(2N)$ (maximum), respectively, where N is the number of trials over which each rate was calculated (Macmillan & Creelman, 2005). The ANOVA results are reported for statistically significant results, with some descriptive values highlighting notable trends.

Results

Response time. There was no significant difference in response time (RT) between accurate and inaccurate verbal responses. Therefore, the following analysis combines both types of responses. Overall, response time was significantly affected by age, $F(2, 33) = 10.142$, $p < .001$, $\eta_p^2 = 0.381$, and cue combination, $F(6, 198) = 91.193$, $p < .001$, $\eta_p^2 = 0.734$. Response times for the younger adult group (mean = 387.20 milliseconds, standard error of the mean: *SEM* = 19.06) were significantly shorter than for both older working adults (mean = 547.77 milliseconds, *SEM* = 20.67; $p = .002$) and older retired participants (mean = 553.40 milliseconds, SEM = 21.29; $p = .001$), Figure 2. No significant difference was found between the two older adult groups ($p = .990$).

With respect to cue combination, response times to bi- and trimodal cues were shorter compared to single (unimodal) signals. Also, across all age groups, response times to trimodal cues (mean RT = 457.73 milliseconds, *SEM* = 18.07) were significantly shorter than for bimodal cues (mean RT = 475.34 milliseconds, *SEM* = 18.41), followed by unimodal cues (mean RT = 529.69 milliseconds, *SEM* = 15.81; $p < .002$ in all cases). (See Tables 4–6 for pairwise comparison trends for each cue modality combination.) No Age × Cue combination interaction was observed.

Hit rate. There was a significant main effect of age, $F(2, 33) = 4.090$, $p < .001$, $\eta_p^2 = 0.199$, and cue combination, $F(6, 198) = 12.258$, $p < .001$, $\eta_p^2 = 0.271$, on response accuracy. The percentage of incorrect responses for the older retired adult group was significantly higher compared to both the younger and older working adult groups. Specifically, retired individuals responded incorrectly to 5.1% of all cases (119/2,347 cues), compared to 1% (23/2,351 cues) for younger adults and 3.3% (77/2,352 cues) for older working adults.

For cue combinations overall, hit rate for the **VAT** combination (hit rate = 92.8%, *SEM* = 1.7%) was significantly lower than for **V** (hit rate = 99.6%, *SEM* = 0.19%, $p = .004$), **A** (hit rate = 99.8%, *SEM* = 0.11%, $p = .003$), **T** (hit rate = 99.8%, *SEM* = 0.20%, $p = .003$), and **VT** (hit rate = 98.3%, *SEM* = 0.64%, $p = .032$). Similarly, hit rate for the **AT** pair (hit rate = 97.9%, *SEM* = 0.52%) was significantly lower than for **V**, **A**, and **T**. A significant Age × Cue combination interaction, $F(12, 198) = 2.127$, $p = .017$, $\eta_p^2 = 0.271$, was found also such that for older adults, accuracy significantly decreased as the number of signals increased. The aforementioned effects were more pronounced for the retired older adult group (i.e., correct response rate for **V** = 99.7%, **A** = 99.7%, **T** = 97.3%, **VA** = 96.1%, **VT** = 92.2%, **AT** = 91.6%, and **VAT** = 87.8%; see Figure 3).

Correct rejection. Correct rejections were not affected by age, $F(2, 33) = 2.501$, $p = .097$, $\eta_p^2 = 0.132$, or cue combination, $F(12, 198) = 0.905$, $p = .547$, η_p^2 0.158, and there was no Age × Cue combination interaction.

Sensitivity. Sensitivity was significantly affected by age, $F(2, 33) = 4.740$, $p = .016$, $\eta_p^2 = 0.223$, and cue combination, $F(6, 198) = 11.185$, $p < .001$, $\eta_p^2 = 0.253$. Younger adults ($d' = 4.142$, *SEM* = 0.062) were better able to distinguish between signal and noise compared to the older retired ($d' = 3.876$, *SEM* = 0.062) group only. In terms of cue combinations, all participants were better able to differentiate single stimuli compared to doubles and triplets (see Tables 4–6 for pairwise comparison summary).

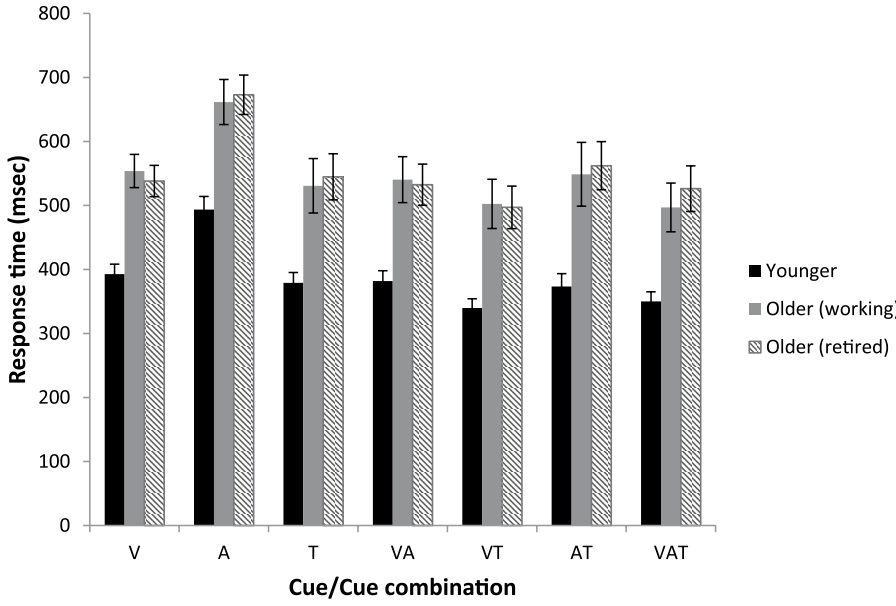

Figure 2. Response time as a function of age and cue/cue combination for Experiment 1 generic task (error bars represent standard error of the mean = *SEM*).

There was also a significant Age × Cue combination interaction, $F(12, 198) = 1.941$, $p = .032$, $\eta_p^2 = 0.105$. Within the older retired group, sensitivity was significantly lower for both the **VAT** ($d' = 3.536$, $SEM = 0.22$) and **AT** ($d' = 3.657$, $SEM = 0.19$) cue combinations compared to both **V** ($d' = 4.176$, $SEM = 0.025$) and **A** ($d' = 4.200$; $SEM = 0$, $p < .05$ in all cases). Within the older working group, sensitivity was significantly lower for the **AT** pair ($d' = 3.633$, $SEM = 0.15$) than for all other stimuli ($p < .05$) except **VAT** and for the **VAT** triplet ($d' = 3.676$, $SEM = 0.11$) compared to **V** ($d' = 4.151$, $SEM = 0.033$, $p = .076$, marginally different), **A** ($d' = 4.245$, $SEM = 0.076$, $p = .004$), and **T** ($d' = 4.339$, $SEM = 0.093$, $p = .011$).

Response bias. A significant main effect of cue combination on response bias, $F(6, 198) = 12.500$, $p < .001$, $\eta_p^2 = 0.275$, and a significant Age × Cue combination interaction, $F(6, 198) = 2.381$, $p = .017$, $\eta_p^2 = 0.114$, were found. Age alone did not significantly affect response bias. Overall, participants were more conservative in their responses to bi- and trimodal cues compared to single cues. In particular, in the **VAT** condition ($\beta = 2.762$, $SEM = 0.377$), participants needed much more evidence that all three stimuli were present before responding compared to all other cue combinations (mean $\beta = 1.172$, $SEM = 0.942$, $p < .05$ in all cases). This effect was more pronounced for older retired individuals (i.e., mean β for **VAT** = 3.74 compared to **V** = 0.96, **A** = 1.0, **T** = 0.88, **VA** = 1.98, **VT** = 1.52, and **AT** = 0.91).

Experiment 1 Summary

Response times and accuracy were affected by both age and cue combination. On average, both older adult groups' response times were 1.4 times longer than the younger group. Generally, 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). Response times to auditory signals were longer compared to the other unimodal stimuli.

For accuracy, no group achieved an overall 100% correct response rate. More incorrect responses were given for combined signals as opposed to single stimuli. This effect was more pronounced in retired older adults who were more than 5 times as likely to miss one cue (119 vs. 23 misses) and more than 1.5 times as likely to miss more than one cue (77 vs. 23 misses) compared to their older working and younger

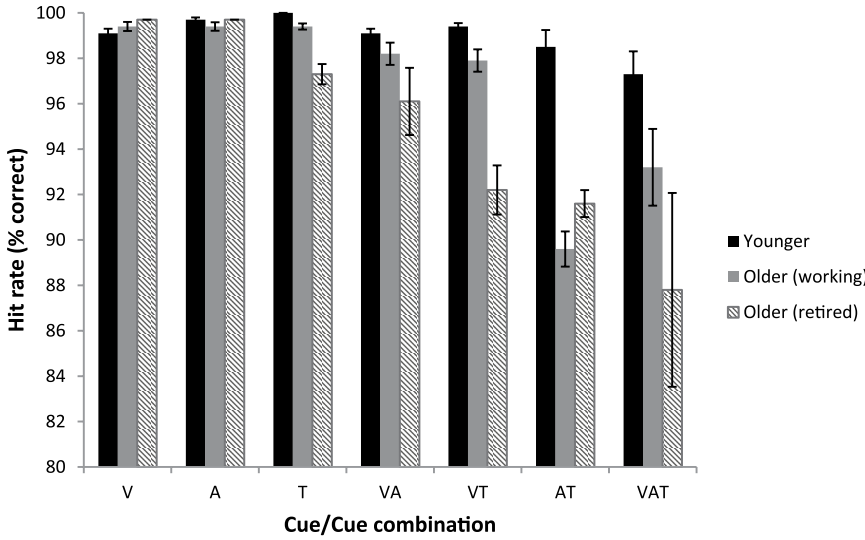

Figure 3. Hit rate (percentage of correct responses) as a function of age and cue/cue combination for Experiment 1 generic task (error bars represent standard error of the mean = *SEM*). Hit rate axis begins at 80%.

counterparts, respectively. In particular, more than half of their errors for the **VAT** combination involved the failure to report the tactile cue. For **AT** pairs, approximately 25% to 30% of all errors made by retired adults were the false reporting of a light (**V**) even though none was present.

Experiment 1 represents a critical first step toward identifying limits of multisensory information processing. However, most real-world environments do not afford people the ability to focus only on a single task as participants in this study did. Therefore, Experiment 2 examined the detection of multiple cues/cue combinations while participants were performing a concurrent task (i.e., driving a simulated vehicle).

EXPERIMENT 2

In recent years, multimodal displays have been introduced to a variety of domains, including the modern car cockpit. In-vehicle assistive technologies, such as blind spot monitors, reversal assistance, and collision warnings, each are associated with different notifications and alerts. Occasionally, drivers may be faced with two or more of these alerts at the same time while having to maintain control of the vehicle. In addition to requiring multitasking, driving is an activity that is being performed by a wide range of age groups, including the elderly. Therefore, Experiment 2 was conducted in the context of a driving simulation. The hypotheses for this study overlapped with those in Experiment 1: (1) Performance (detection rate and response time) will suffer significantly if a person is asked to notice and report three (compared to two) simultaneous multimodal signals, and (2) this performance decrement will be more pronounced in older participants than younger adults. In addition, detection performance was predicted to deteriorate further in the presence of the driving task, especially for older adults.

Methods

Participants. The same 36 participants from Experiment 1 also volunteered for this study, which took place approximately 6 months later. The requirements for participation were the same in both experiments. In addition, all participants were required to have a valid U.S. driver's license. They were asked for background information regarding their driving experience and features of their current vehicles that present information in visual, auditory, and/or tactile forms, most notably: GPS, rear/sideview cameras, lane departure, blind spot notification, and

collision avoidance. The number of in-vehicle systems reported did not differ between age groups (mean = 14; GPS and cameras were most common). Older participants were asked to report any perceptual and/or cognitive changes they noticed in themselves over the years (especially driving-related) and how they try to overcome these limitations. Seventy-one percent (17/24) explained that increased sensitivity to headlights of approaching traffic at night causes them to limit nighttime driving. Participants were compensated for their time in the experiment. To ensure that participants assigned the same priority to all tasks, a monetary bonus was awarded for outstanding performance on both the driving and signal detection tasks.

Apparatus. The stimuli were the same as those used in Experiment 1: a blue LED (visual stimulus), 350-Hz monotone beeps (auditory cues), and 250-Hz vibrations presented via C-2 tactors (tactile cues).

Experiment 2 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 approximately 3.5 feet in front of the participant (see Figure 4). The driving environment 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.

Design. As in Experiment 1, the study employed a 3 (age group) × 7 (cue/cue combination) full factorial design. Age was a between-subject variable, and cue combination was a within-subject variable.

Procedure. After signing the consent form, participants were asked to complete a biographical data form that focused on their driving experience. Next, each participant was administered the two divided attention assessments as in Experiment 1. The full range of multimodal stimuli was introduced, and participants were asked to perform the same cross-modal matching task as in Experiment 1. They then completed three separate training sessions to become familiar with the tasks and required responses (approximately 15 minutes):

Figure 4. Experiment setup with multimodal stimulus and apparatus for Experiment 2 driving study.

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 (facing the driver; see Figure 4) using their thumbs and then verbalize the cue(s) detected. To proceed, participants were required to achieve a 90% accuracy level on this task.
2. Driving task: For the driving task, participants were first asked to position themselves similar to the manner in which they drive normally. Next, they were instructed to maintain a constant speed of 40 mph (or 58.67 ft/s for analysis purposes) and also remain in the center of the lane (6 feet from both right and left lane boundaries) at all times during the scenario. Before proceeding, participants were required to demonstrate 90% compliance with average speed and lane position requirements.
3. Driving and detection task: The final part of the training session combined the two tasks. Participants were explicitly told that they should not prioritize one task over the other.

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 and speed requirements, participants were presented with 28 instances of each cue combination (a total of 196 trials per person; 49 cues in 4 separate blocks that lasted about 5 minutes each). Cues/

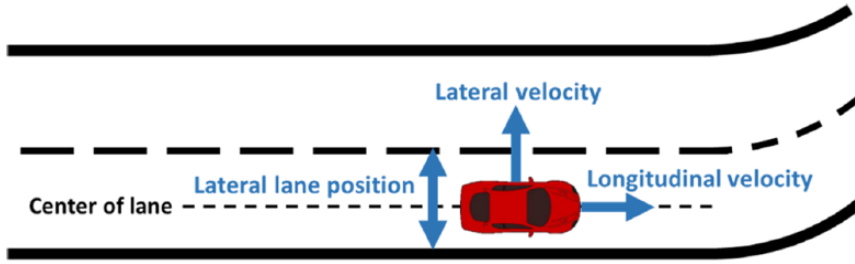

Figure 5. Illustration of driving performance measures used in Experiment 2.

cue combinations were presented on average once every 7 seconds (range, 4–10 seconds). Each cue duration was 1 second. Participants were instructed to press either response button on the steering wheel 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. The order in which the cue combinations were presented was counterbalanced. Following the experiment, participants completed a debriefing session where they were asked to comment on their experiences, including any strategies they used for driving the vehicle and detecting the stimuli, and provide feedback about the experiment. The experiment lasted approximately a total of 2 hours.

Dependent measures. The dependent measures for the detection task were the response time and accuracy of responses to each cue/cue combination (as described in Experiment 1). Also, signal detection theory analysis was performed. For the driving task, the following commonly used driving performance measures were recorded (see Figure 5):

1. forward (longitudinal) velocity (FV): the forward speed of the vehicle (feet/second);
2. lateral velocity (LV): the horizontal component of speed of the vehicle with respect to the center of the lane (feet per 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 driving line (feet; 6 feet is center of lane, 0–6 feet = right of center, 6–12 feet = left of center; total width of lane = 12 feet).

For each of the aforementioned measures, absolute maximum deviations (magnitude of deviation in either direction) were calculated. To do this, the mean (average) for each driving measure was calculated over a time period of 3 seconds immediately before and 3 seconds immediately after the initiation of cue/cue combination. Then, the difference between "after" and "before" was recorded. A resulting value other than zero suggested that the cue(s) affected driving performance. No cue was presented while participants were entering or driving inside of curves.

Data analysis. As in Experiment 1, data were analyzed using a mixed-model repeated measures ANOVA as well as two-tailed Fisher's LSD post hoc tests and paired comparisons. Bonferroni corrections were applied for multiple statistical tests. Significance was set at $p < .05$, and partial eta squared (η_p^2) was used as a measure of effect size. Also similar to Experiment 1, for signal detection analysis, a standard correction method was used when needed.

Results

Response time. No significant difference in response time between accurate and inaccurate verbal responses was found. Response time was significantly affected by age, $F(2, 33) = 4.982$, $p = .013$, $\eta_p^2 = 0.232$, and cue combination, $F(6, 198) = 15.742$, $p < .001$, $\eta_p^2 = 0.323$ (see Figure 6). The average response time for the younger adult group (mean = 520.89 milliseconds, *SEM* = 27.03) was significantly shorter than for the older retired group only (mean = 773.24 milliseconds, *SEM* = 52.47, $p = .012$). Also, across all age groups, response times to trimodal cues (mean RT = 620.04 milliseconds, *SEM* = 38.34) were significantly shorter than for bimodal cues (mean RT = 647.84 milliseconds, *SEM* = 36.14), followed by unimodal cues

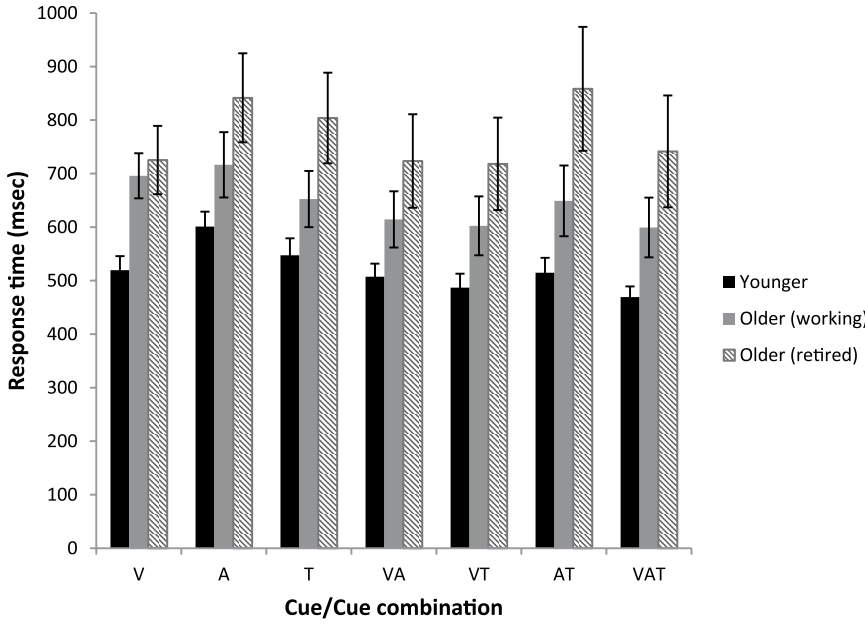

Figure 6. Response time as a function of age and cue/cue combination for Experiment 2 driving task (error bars represent standard error of the mean = *SEM*).

(mean RT = 690.83 milliseconds, *SEM* = 30.195; $p < .03$ in all cases). (See Tables 4–6 for pairwise comparison summary.)

Hit rate. There was a significant main effect of cue combination, $F(6, 198) = 12.258$, $p = .001$, $\eta_p^2 = 0.107$, and a marginally significant effect of age, $F(2, 33) = 2.794$, $p = .076$, $\eta_p^2 = 0.145$, on hit rate.

For cue combination, hit rate was significantly lower for **VAT** (hit rate = 92.8%, *SEM* = 1.6%) than for **V** (hit rate = 99.7%, *SEM* = 0.2%, $p = .002$), **T** (hit rate = 99.2%, *SEM* = 0.4%, $p = .007$), and **VT** (hit rate = 97.4%, *SEM* = 0.8%, $p = .30$). This was true also for **AT** (hit rate = 96.7%, *SEM* = 0.7%) compared to **V** ($p = .007$) and **T** ($p = .011$) (see Figure 7).

For age, the percentage of incorrect responses given by the older retired adult group was higher compared to both the younger and older working adult groups. In particular, retired participants responded incorrectly in 5.2% of all cases (122/2,346 cues) compared to 1.2% (28/2,352 cues) for younger adults and 2.8% (66/2,351 cues) for older working adults.

Correct rejection. Correct rejections were not affected by age, $F(2, 33) = 0.949$, $p = .398$, $\eta_p^2 = 0.054$, or cue combination, $F(6, 198) = 1.214$, $p = .275$, η_p^2 0.069.

Sensitivity. Sensitivity was significantly affected by age, $F(2, 33) = 3.707$, $p = .035$, $\eta_p^2 = 0.183$, and cue combination, $F(6, 198) = 9.915$, $p < .001$, $\eta_p^2 = 0.231$. Younger adults ($d' = 4.1$, *SEM* = 0.073) were better able to distinguish between signal and noise compared to both older working ($d' = 3.971$, *SEM* = 0.073) and older retired ($d' = 3.819$, *SEM* = 0.073) groups across all trials. For cue combinations, all participants were better able to differentiate single stimuli compared to doubles and triplets (see Tables 4–6 for pairwise comparison trends).

Response bias. Significant main effects of cue combination, $F(6, 198) = 12.850$, $p < .001$, $\eta_p^2 = 0.280$, and age, $F(2, 33) = 4.210$, $p = .024$, $\eta_p^2 = 0.203$, on response bias were found. 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 ($p < .05$ in all cases), participants needed more evidence that all three stimuli were present before responding. Older retired adults displayed a significantly higher response bias ($\beta = 1.993$, *SEM* = 0.199)

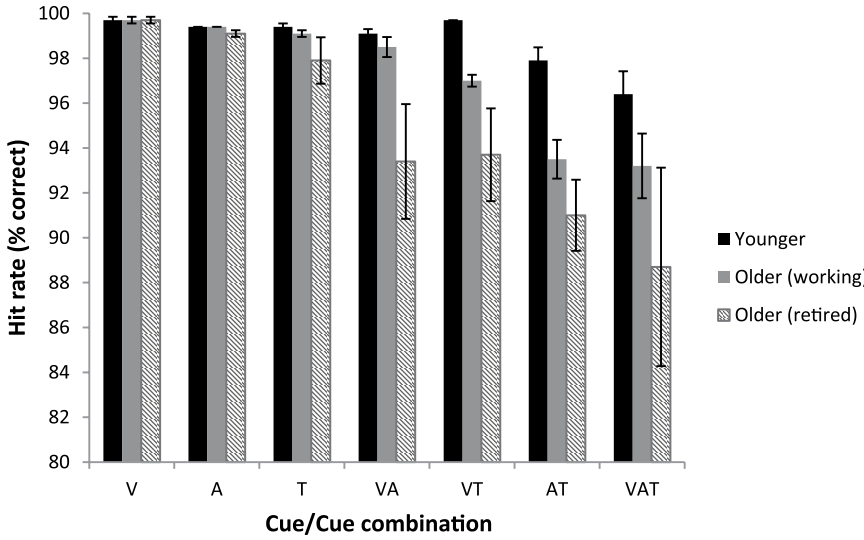

Figure 7. Hit rate (percentage of correct responses) as a function of age and cue/cue combination for Experiment 2 driving task (error bars represent standard error of the mean = *SEM*). Hit rate axis begins at 80%.

TABLE 3: Average Speed and Lane Position During Driving Simulation When No Cue Was Present for Each Age Group

Age Group	Speed (Feet per Second)	Lateral Lane Position (Feet)
Younger	54.63 (0.43)	6.11 (0.08)
Older (working) adult	55.03 (0.81)	6.11 (0.14)
Older (retired) adult	55.98 (0.89)	6.16 (0.10)

Note. Requirements: speed = 58.67 ft/s; lateral lane position = 6 ft. Standard error of mean in parentheses.

compared to the younger (β = 1.230, *SEM* = 0.199, $p = .032$) participants.

Driving performance. No significant difference was found between age groups for the average forward velocity (speed) and lateral lane position for the accumulation of driving periods during which no cue was present (Table 3).

Forward (longitudinal) velocity. The average change in forward velocity was significantly affected by cue combination only, $F(6, 198) = 8.026$, $p < .001$, $\eta_p^2 = 0.196$ (see Figure 8). Participants changed their speed the most after being presented with **VAT** (by 1.07 ft/s, *SEM* = 0.41) compared to **V** (0.919 ft/s, *SEM* = 0.41, $p = .002$), **A** (0.849 ft/s, *SEM* = 0.44, $p < .001$), **T** (0.9 ft/s, *SEM* = 0.05, $p = .007$), and **VA** (0.78 ft/s, *SEM* = 0.46, $p < .001$).

Lateral velocity. The magnitude of changes in lateral velocity was affected by age, $F(2, 33) = 5.975$, $p = .006$, $\eta_p^2 = 0.266$, but not cue combination. 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; $p < .05$ in both cases). Changes in lateral velocity did not differ between the two older adult groups.

Lateral lane position. Similar to lateral velocity, deviations in lane position 3 seconds after the initiation of a cue were significantly affected by age only, $F(2, 33) = 11.432$, $p < .001$, $\eta_p^2 = 0.429$. 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

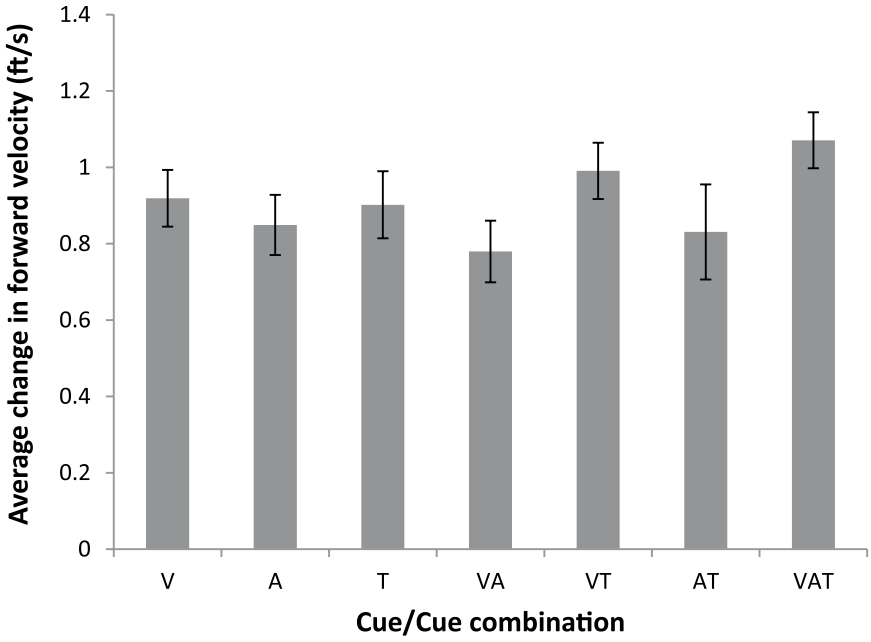

Figure 8. Average change in forward (longitudinal) velocity as a function of cue/cue combination for all participants (error bars represent standard error of the mean = *SEM*).

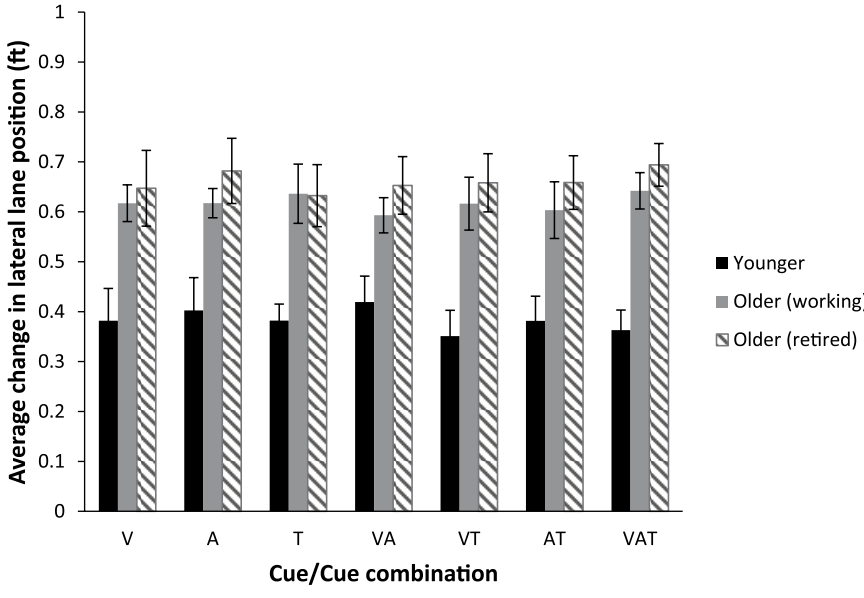

Figure 9. Average change in lateral lane position as a function of age and cue/cue combination (error bars represent standard error of the mean = *SEM*).

participants) compared to the younger group (0.383 ft.; $p < .003$ in both cases, see Figure 9). Lane position deviations did not differ between the two older adult groups.

Experiment 2 Summary

Similar to Experiment 1, response times and accuracy were affected by age and cue combination. During the driving task (Experiment 2), both

TABLE 4: Summary of Main Effect Trends of Age on Response Time and Signal Detection Analysis Measures for Experiments 1 and 2

Metric	Experiment 1	Experiment 2
Response time	Younger < older working, retired	Younger < older working, retired
Hit rate	Older retired < younger, older working	Older retired (marginally) < younger, older working
Correct rejection rate	—	—
Sensitivity (d')	Younger > older retired	Younger > older working, retired
Response bias (β)	—	Older retired > younger

TABLE 5: Summary of Main Effect Trends of Cue/Cue Combination on Response Time and Signal Detection Analysis Measures for Experiments 1 and 2

Metric	Experiment 1	Experiment 2
Response time	**A** > all combinations **VT** < **V**, **T**, **VA**, **AT** **VAT** < **V**, **T**, **VA**, **AT**	**A** > all combinations **VT** < **T**; **VT**, **VAT** < **AT**
Hit rate	**AT** < **V**, **A**, **T**; **VT** < **A** **VAT** < **V**, **A**, **T**, **VT**	**AT** < **V**, **T** **VAT** < **V**, **T**, **VT**
Correct rejection rate	–	–
Sensitivity (d')	**VT** < **A**, **T**; **AT** < **V**, **A**, **T**, **VA** **VAT** < **V**, **A**, **T**, **VA**	**VAT** < all combinations; **AT** < **V**, **T**, **VA**; **VT** < **V**
Response bias (β)	**VAT** > all combinations	**VAT** > all combinations

Note. **V** = visual; **A** = auditory; **T** = tactile.

TABLE 6: Summary of Interaction Effect Trends of Age and Cue/Cue Combination on Response Time and Signal Detection Analysis Measures for Experiments 1 and 2

Metric	Experiment 1	Experiment 2
Response time	—	—
Hit rate	Older retired only: **VT** < **V**, **A** **VAT** < **V**, **A**, **T**, **AT**	—
Correct rejection rate	—	—
Sensitivity (d')	**AT**: older retired < younger Older retired only: **VT**, **AT**, **VAT** < **V**, **A** Older working only: **AT** < **V**, **A**, **T**, **VA**, **VT**; **VAT** < **V** (marginally), **A**, **T**	—
Response bias (β)	Older retired only: **VAT** > all combinations	—

Note. **V** = visual; **A** = auditory; **T** = tactile.

older adult groups responded 1.5 times slower than the younger group. Across all age groups, response times to triplets (620 milliseconds) were faster than for pairs (648 milliseconds), which in turn were responded to shorter than single cues (691 milliseconds). Again, auditory signals resulted in the longest unimodal response times.

Also as in Experiment 1, no group achieved a 100% hit rate. There was larger variability in responses within the older retired group (reflected in error bars in Figure 7), resulting in only marginally significant main effects. Yet by count, the highest number of errors among groups for all bi- and trimodal combinations were made by older retired participants, and the same general trends were observed in both experiments. In particular, this group falsely reported the presence of **V** in 53% of all errors in the **AT** condition and also failed to notice **T** in 68% of errors for the **VAT** combination. A new observation during the driving task, however, was that for stimulus pairs involving **V** (i.e., both **VA** and **VT**), 86% of errors for retired individuals consisted of reporting only **V**.

Comparison Between Experiments 1 and 2

Overall, response times to cues were significantly shorter in Experiment 1 (496.11 milliseconds) than in Experiment 2 (662.29 milliseconds), representing a 33% difference ($p < .001$). However, no difference in hit rate was found. Tables 4 through 6 summarize the main and interaction effects and trends of age and cue combination on detection performance for the generic (Experiment 1) and driving (Experiment 2) task studies.

GENERAL DISCUSSION

The goal of this study was twofold. First, we sought to establish how reliably people notice and process more than two nonredundant cues that appear concurrently in the visual, auditory, and tactile modalities. Our second goal was to investigate how aging and concurrent task demands modulate this ability. Two experiments were conducted, one requiring cue detection only, while the second added a driving task. In both experiments, response times and accuracy were affected by age and cue modality/modality combination. Also, performance on the driving task suffered when participants were asked to detect multimodal stimuli.

Response Time

As expected, response times of the two older adult groups were longer (1.44 times longer on average) than that of the younger participants to all cues/cue combinations. Similar time differences have been reported in previous research that investigated age-related differences in responses to combined (bimodal) cues (e.g., Laurienti, Burdette, Maldjian, & Wallace, 2006; Mahoney, Li, Oh-Park, Verghese, & Holtzer, 2011; Mahoney, Verghese, Dumas, Wang, & Holtzer, 2012) and speeds of information processing in general (e.g., Birren & Schaie, 2005; Craik & Salthouse, 2011; Fisk et al., 2009).

Across all age groups in both experiments, response times to triplets tended to be shorter than to stimulus pairs, followed by single cues. The performance gains observed for multiple signals are one of the reasons why researchers have employed redundant cue combinations in the past (e.g., Hecht, Reiner, & Karni, 2008b; Miller, 1982; Van Erp & Van Veen, 2004). Even though the signals employed in the current study were not completely redundant, the observed benefits were the same as redundant cues. This suggests that presenting participants with two or more concurrent inputs generally increases vigilance/alertness and attention to signals (Bertelson & Tisseyre, 1969; Hecht et al., 2008b; Sanders, 1980). Some researchers attribute this effect to the simultaneous activation of multiple sensory receptors (e.g., Hecht et al., 2006). However, the results of our study highlight an alternative explanation for these multisensory performance gains, that is, response time to combined cues is being dominated by the sensory stimulus with the fastest conduction velocity. For example, a visual-tactile stimulus pair is responded to faster than a visual signal alone because the tactile signal (with shorter stimulation rate) is noticed first and immediately responded to.

In both experiments, response times to auditory signals were longer compared to the two other unimodal stimuli, even though they are traditionally responded to faster than visual stimuli (e.g., Hecht et al., 2008a, 2008b; Scott & Gray, 2008). This apparent contradiction may be explained by a bias due to the pink noise, and its associated low-frequency tone, that was played over the stereo headphones. It may have caused a slight processing delay as participants tried to distinguish the auditory signal from the back-

ground noise. Also, response times to visual cues in this experiment may not have been longer compared to other stimuli (as traditionally observed) because these cues were perceived in peripheral vision. Thus, according to multiple resource theory (MRT; Wickens, 1980, 2008), these signals did not interfere with the processing of the focal visual information required for the driving task.

Response times to cues in Experiment 2 (driving task) were significantly longer than in Experiment 1, likely due to the additional attentional demands associated with the driving task. In Experiment 1, participants' only task was to monitor for and respond to each signal. In contrast, in Experiment 2, attentional resources were now consumed by the continuous visuospatial task of driving the vehicle, which, also according to MRT, may have resulted in resource competition in terms of modality (vision), processing stage (perception, cognition, and response), and response type (manual responses both for driving and reporting cue detection).

Accuracy

One important distinction between our approach and previous work is that the current study employed cross-modal matching prior to each experiment. This was done to avoid confounding modality with signal salience and maximize signal perceptibility for all participants. Yet overall, older retired adults reported more incorrect responses to all bi- and trimodal combinations than the other two groups in both experiments. However, this difference was less pronounced in Experiment 2 due to larger variation within this group. Across both studies, roughly 70% of errors for this group involved the failure to report a tactile cue in the visual-auditory-tactile condition. One reason for this performance breakdown could be their very limited exposure to signals in this modality. In contrast, younger participants are more frequently exposed to touch technology in everyday life, such as video games or cellular phones. However, the relative novelty of tactile signals should have also led to a higher detection rate in older adults, but this effect was not observed. It is also plausible that older individuals were aware of the presence of multiple signals but might have struggled to recall the exact modality and instead reported more conventional (visual and auditory) stimuli only. The higher prevalence of this phenomenon in older participants further implies their difficulty with divided attention in general (Craik & Salthouse, 2011; McDowd & Craik, 1988). Another possible reason for this failure to report the tactile cue, particularly for Experiment 2, may be cross-modal spatial links in attention (e.g., Ferris & Sarter, 2008; Spence & Driver, 1997a). In other words, in this study, visual cues and the driving task were presented on/below the monitor in front of the participants, while vibrations were applied to their back. The tactile signal might have been noticed and reported more often if stimuli had been presented to frontal areas of the body with lower perceptual thresholds, and thus higher sensitivity, such as the fingers, hands, or face (Sherrick & Cholewiak, 1986).

Across both experiments, an unexpected finding for **AT** pairs in older retired adults was that 37% of all errors involved falsely reporting a **V**. In 93% of 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 second 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 less than 7 seconds. Given this timing, the brightness of the light with respect to the darkness of the environment, and the slower processing speed of visual information witnessed in older adults, a persistence effect (Coltheart, 1980; Di Lollo, Arnett, & Kruk, 1982; Hawthorn, 2000), might have also occurred in which the sensation of a previously presented visual stimulus is still present. This combination of factors may have triggered an automatic response or recency effect (Hawthorn, 2000; Logie, 1995) in the visual modality, which has been most prevalent in elderly participants. One other possible interpretation for this finding is that older individuals might have simply erred on the side of caution and deemed the slightest sensation (e.g., an eye blink) to be a signal.

In the driving study, for stimulus pairs involving **V** (both **VA** and **VT**), 86% of errors in the

older retired group consisted of reporting only the **V**. This result is similar to Hecht and Reiner (2009), who found that 88% and 78% of errors for **VA** and **VH(aptic)**, respectively, involved missing the auditory or haptic signal. 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 (Sinnett, Spence, & Soto-Faraco, 2007; Ward, 1994) or a trimodal visual-auditory-tactile cue (Hecht & Reiner, 2009). Another possible reason may be modality priming, a top-down influence on attention. Since the driving task was primarily visual, 9 of 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).

With respect to detection rates, one could speculate that the modest performance difference between the two older populations may relate to activity after retirement. Although 11 of 12 retired adults reported involvement in weekly exercise and community/volunteer work, the level of engagement in these activities may not provide equivalent occupational cognitive demands to sustain pre-retirement functioning. However, more investigation is needed to confirm this hypothesis.

Finally, hit rates did not differ between the two experiments. One likely explanation for this finding is a ceiling effect due to the level of difficulty of the driving task. It did not involve surrounding traffic, additional road scenery, or additional sounds/vibrations.

Driving Performance

Lane position and lateral velocity. For all cue combinations, changes in lane deviations and lateral velocity were significantly greater for the two older adult groups compared to the younger group. These findings 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. They explained that 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—leading to a greater lane deviation. Also, poorer perceptual feedback and increased noise in motor pathways have been shown to lead to slower movement speeds and less precision in the control of movements in older adults (e.g., Birren & Schaie, 2005; Craik & Salthouse, 2011; Fisk et al., 2009; Seidler et al., 2010; Smith, Sharit, & Czaja, 1999). These issues could have resulted in delayed correction (recovery) times after senior participants had been presented with a cue/cue combination. In this particular case, once they had deviated from their original lane position, it took them even longer to get back to their starting point. A similar effect was observed in earlier work where, compared to younger participants, older adults were 17% less accurate in maintaining proper lateral lane after being presented a choice-reaction time task (Ponds, Brouwer, & van Wolffelaar, 1988).

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). Here, task performance suffered as a result of an upper processing limit in attentional resources.

Limitations

Given the considerable variability in cognitive and physical capabilities reported in older adults of the same age group (Hultsch, MacDonald, & Dixon, 2002; Oakley, 2009; Rogers, 1997), a larger sample size would have been more desirable.

Second, the simulated task in Experiment 2 was not fully representative of real challenges faced by drivers on a daily basis. The intent of

this experiment was to provide baseline performance data for the detection and driving tasks in the absence of other stimuli. However, future research should explore more realistic driving scenarios that increase overall workload and divided attention demands. Similarly, the multimodal signals in this research did not have any driving-related meaning, which may have affected response times, hit rates, and driving performance. Manipulating task relevance, signal semantics, and response type may result in different strategies employed by participants. Another potential shortcoming of the study relates to the stability of the tactile cue. Even though the belt was fastened tightly around participants' waist, involuntary movements made while seated could have altered the perceived magnitude of vibrations. Note, however, that no major movements or sudden drops in detection performance were observed by the experimenter.

Lastly, this study did not collect eye-tracking data, which can highlight participants' visual behavior and help explain attention allocation. For example, these data can confirm the comments made by older participants who explained that they focused mainly on the forward visual scenery during the driving task.

CONCLUSION

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 adults. Overall, detection performance in this study was rather good (the lowest detection rate was approximately 88%) as a result of the relative frequency of signals to be detected. However, in terms of operational significance, missing even just one infrequent signal in the context of real-life situations could result in a near crash or an accident.

Additional research is needed prior to adopting these results, which, given the noted limitations of this study, should be interpreted with caution. Still, the observed performance decrements point to potential limits in increasing the quantity of unrelated information presented to (older) operators at the same time. In data-driven, demanding environments for which this approach is not feasible, the development of context-sensitive adaptive displays that can automatically adjust the timing, salience, amount, modality, location, or frequency information by monitoring attentional states and performance (Hameed & Sarter, 2009; Li, Wickens, Sarter, & Sebok, 2014; Parasuraman, Sheridan, & Wickens, 2000) may serve as a countermeasure. Finally, this research can be used to inform the design of vehicles with varying levels of autonomy and improve overall operator and public safety, which can in turn support greater independence and quality of life for a wide range of age groups.

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KEY POINTS

- Response times to combined multimodal cues were shorter than for single cues, but accuracy suffered.
- Older retired adults most often missed tactile cues when they were presented with visual and auditory cues and also falsely reported the presence of a visual signal when presented with auditory and tactile cues.
- Performance on the continuous driving task suffered the most for older adults when presented with any modality combination and for all participants when presented with the combined visual-auditory-tactile stimulation.
- Signal detection rates were not reduced when participants had to perform the driving task, possibly due to the relatively low attentional demands associated with the driving scenario.

- Adaptive displays that adjust signal timing and/or salience, via adaptive displays, may be beneficial in supporting attention management, especially for older adults.

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Brandon J. Pitts is an assistant professor in the School of Industrial Engineering and a faculty associate with the Center on Aging and the Life Course at Purdue University. He earned his PhD in industrial and operations engineering from the University of Michigan in 2016.

Nadine Sarter is a professor in the Department of Industrial and Operations Engineering and director of the Center for Ergonomics at the University of Michigan. She received her PhD in industrial and systems engineering from Ohio State University in 1994.

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