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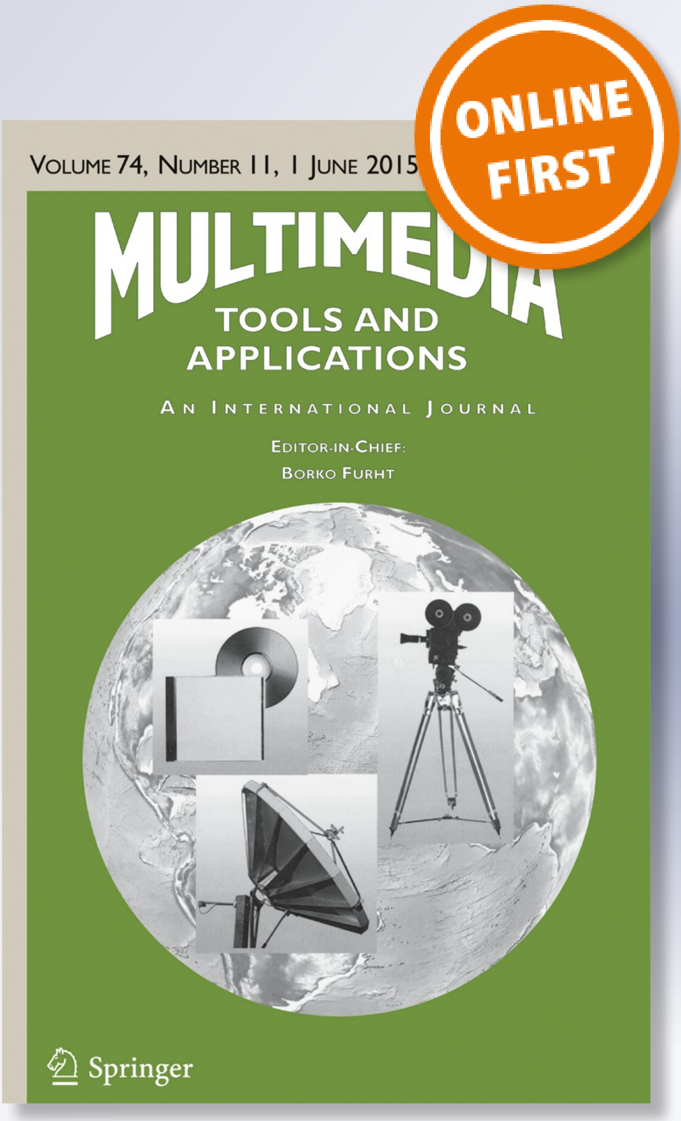
Multimedia Tools and Applications
An International Journal

ISSN 1380-7501

Multimed Tools Appl
DOI 10.1007/s11042-015-2712-4



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Augmenting human senses to improve the user experience in cars: applying augmented reality and haptics approaches to reduce cognitive distances

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Received: 20 October 2014 / Revised: 2 March 2015 / Accepted: 21 May 2015

Abstract Augmenting people's senses with computational support can improve the ability to perceive information and perform tasks. However, the impact of such augmentation may fluctuate according to user context, thereby impacting the quality of a user experience. In this paper, we present two systems that assess the in-situ effects of augmenting senses using Augmented Reality and Haptic technologies. We demonstrate that sensory augmentation systems can improve performance when users are multitasking; however, a hybrid assessment, including eye tracking and psycho-physiological measurement, reveals that the benefits and costs of such systems can differ depending on the demographics of a population with different cognitive capabilities. For elder adults, sensory augmentation improved perception for responding to local incidents in the physical space, but a richer intervention using sensory augmentation (visual, auditory, and haptic) strains cognitive load. For younger adults, additional modes for providing sensory information increased attentiveness for performing tasks, but can lead to overloading of already used sensory channels. Thus, sensory augmentation was more advantageous for improving global awareness for situated physical space, rather than responding to local incidents.

Keywords Human-computer interaction · Automotive user interfaces · Multisensory interaction · Sensory augmentation systems

1 Introduction

Human cognitive capacity is finite [47]. Attending to a task reduces the cognitive resources available for other tasks. In order to effectively manage this finite capacity in multi-tasking

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situations, it becomes increasingly important to enable intelligent systems to augment our ability to process information, and minimize interfering factors that demand additional mental effort (e.g., extraneous cognitive load in cognitive load theory [40]).

Nowadays, technology enables us to interact with information anywhere, at any time. Much of this technology relies on the manifold benefits of Human-Computer Interaction (HCI) research. However, the increase of mobile and wearable devices in connected environments (e.g., using smartphones or smart watches in a connected car) comes at a cost to attention and cognition. Situational variations in cognitive demands affect the *quality* of a user's HCI experience. For example, in-car navigation systems enhance a driver's situational awareness, but also increase visual distraction and cognitive load [31, 30]. The impact of information arriving in mobile contexts fluctuates according to the limited cognitive resources that remain for secondary tasks, which may lead to attention-impoverished situations. In addition, this may impact the user's ability to apply this information in the completion of her tasks.

User contexts affect an end-user's evaluation of the value of HCI experience because users are often already engaged in a primary task in their physical space. Depending on the relevance of the information provided to a user, the method of conveying that information, and the user circumstances, the distance between physical spaces (i.e., the real world) and virtual information spaces may be small or large. With a large gap, a user may take more time and expend more cognitive effort to transition from one space to another. We refer to this gap as the *cognitive distance* between computing and physical spaces [27].

Cognitive distance is comprised of two types of effort: (a) effort to shift attention from the physical space to the information space, and to then identify the appropriate information, and (b) effort to return to the physical space and apply the extracted information to the task at hand. As the effort required for either component grows, the overall cognitive distance grows (See the dashed line in red in Fig. 1). End-users rely on situated contexts to determine information relevance and more or less appropriate timings for its intervention (i.e., *what to intervene* and *when to intervene* in a given context). In addition, information representation (i.e., *how to intervene*) influences cognitive processing workloads.

One way to minimize cognitive distance for engaging with both spaces is to create *smarter* computing systems (i.e., contextually intelligent) by attacking the issues of *what to intervene* and *when to intervene*. Another way is to create computing systems with greater *affordances* by determining *how to intervene*, which can facilitate human capabilities during HCI. In this paper we examine the latter issue, *how to intervene*, by seeking novel ways to represent information to minimize perceptual and cognitive processing workloads during HCI. We explore how technology-driven sensory augmentation impacts human perception and cognition.

For this, we visit two of our prior studies [27, 30]. In these studies, we explored an automotive context in which the goal is to maintain a safe equilibrium between the benefit of intervened information (i.e., value-to-get) and mental demand associated with its attentional interference (i.e., cost-to-spend). In the studies, we developed two sensory augmentation systems for in-vehicle use: a windshield-based display using Augmented Reality technology and a vibro-tactile steering wheel using Haptic technology. Participants in our studies, younger drivers and elder drivers (over the age of 65), performed driving tasks in a driving simulation that incorporated our sensory augmentation systems. Here we discuss how such context-sensitive augmentation systems can reduce cognitive distance when multitasking in real-world settings.

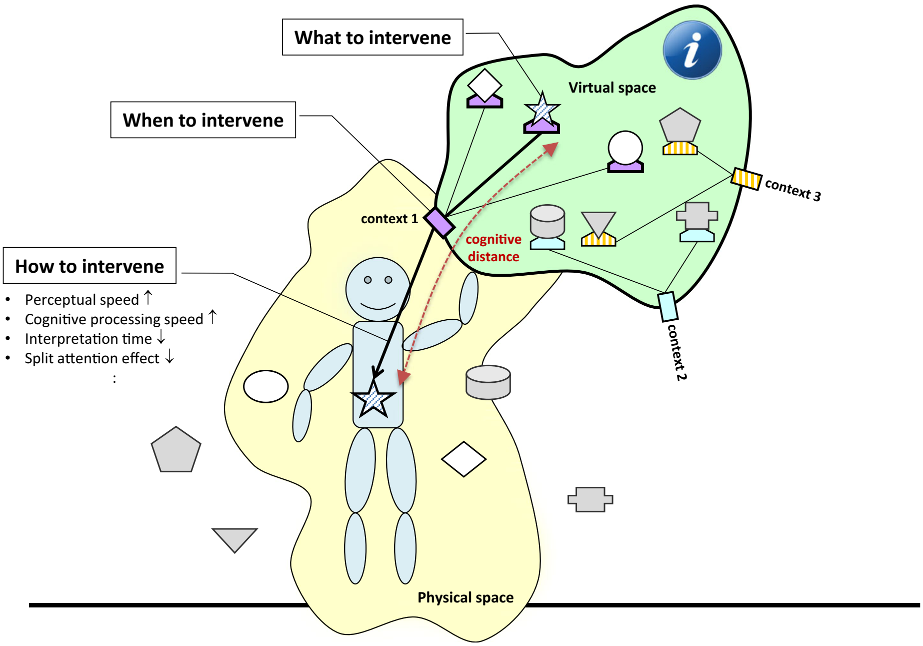


Fig. 1 Context-sensitive cognitive distances between physical space and virtual information space

2 Background work

In this section, we discuss related work on *dual-task paradigms* that represent the real-world scenarios we have replicated in this study; *sensory augmentation* that may improve the HCI experience in overcoming attention-impoverished situations created by the demands of dual-task paradigms; and *sensor-based experience sampling approaches* that can be used to objectively understand real-time variations in attention and cognitive load.

2.1 In-situ dual-task paradigm

In experimental psychology, dual-task paradigms are used to understand how participant responses deteriorate (e.g., lag in reaction time or increase in errors) when using finite cognitive resources to perform two tasks simultaneously [49]. These paradigms have been used to assess attentional capacity or the requirements of working memory processes [15] to estimate the *effort* expended on a primary task (e.g., [42]). The interpretation of dual-task paradigms generally follows the view that human processing resources are limited and sharable across tasks [23, 51].

In conventional dual-task experimentation, secondary interaction demands are designed to interfere with primary tasks by taxing cognitive resources. To be clearly traceable for *post-hoc* analysis (e.g., low vs. high complexity), most secondary tasks are artificial, rather than naturalistic. Dual-task paradigms using short-term memory tests (e.g., Benton visual retention test, *n*-back and digit span tests) or elementary cognitive tasks [17] have been effective in examining cognitive processing elements that mainly interfere with primary task performance. Study participants benefit little from interactions with secondary tasks, which detract from a positive user experience.

On the other hand, demands for peripheral interactions are more complex in the real world. In real-world situations, interference with primary tasks is mostly a side effect of performing the primary task. Therefore, dual-task demands are more sporadic and are often combined with informational interventions. While peripheral interactions still take cognitive resources from the primary tasks to process information, they mostly aim to benefit the user rather than simply detract from cognitive capability. Naturalistic dual-task paradigms always accompany an in-situ trade-off between expected demands (i.e., cost) and benefits (i.e., values).

For example, the in-car navigation scenarios that we explore in this paper augment a driver's cognitive capabilities by improving situation awareness. The driver, however, must be willing and able to accept the augmentation, and, in particular, deal with extraneous cognitive load induced by split attention caused by the augmentation [6]. Prior to interacting with the additional sensory information, drivers must judge whether the expected benefits will be larger or smaller than expected costs at the moment of intervention, which is consciously or subconsciously followed by a transition of overt attention.

Indeed, an individual's visual scan strategy is influenced by the inherent cognitive demands of given tasks. In our prior studies [29], elderly subjects' visual scan strategies were fairly proficient when asked to read dashboard information, though the subjects displayed significant differences when asked to obey route guidance information, as compared to younger drivers. Elder drivers knew when to interact with dashboard displays to perform safe dual-task driving. Also, visual scan performance is influenced by simple changes in the representation of information. Elder drivers, who are more prone to extraneous cognitive load compared to younger drivers, showed significant changes in perceptual performance according to changes in automotive user-interface design elements such as color, size contrast, or visual information clutter [29]. As such, under naturalistic situations of dual-task paradigms, expected benefits and costs vary contextually along with in-situ capability in cognition and attention. In this context, this paper investigates how sensory augmentation systems impacts user experience under a naturalistic dual-task situation.

2.2 Sensory augmentation – substitution or extension

In general, *sensory augmentation* has been explored with two aims: 1) to help people with sensory deficits restore the ability to perceive a certain defective sensory modality by using the existing capabilities of a functional human sensory system (e.g., [9]), or 2) to extend the body's ability to sense aspects of the environment that are not normally perceivable [22].

Sensory substitution systems include braille or speech synthesizers, in which visual information is transformed into touch or hearing modes. Similarly, walking canes transmit surface profile, roughness, and elasticity to the hand to assist the visually-impaired with navigation [22]. Sonar-like ultrasonic ranging sensors enable a glasses-type wearable device (e.g., Wormald Sonicguide) to provide audio information on the azimuth of a physical object and distance by changing inter-aural intensity and frequency [11].

On the other hand, *sensory extension* responds to context-sensitive functional demands for people with normally-functioning sensory systems. That is, sensory extension responds to temporal deficits in one's sensory system due to extraneous factors in a situated environment, perceptual overload due to unintelligent interruption by multimedia information, or cognitive aging. For example, a vibro-tactile glove could provide information about the distance of salient objects in low vision search contexts for firefighters whose visual experience is compromised due to smoke and low ambient light levels [3]. A head-worn display and a jaw-worn microphone-audio set can be used to provide real-time audio and visual augmentation [8], which helps users hear speech selectively by neutralizing background noises and amplifying the chosen speech, or to help users see traces and patterns hidden to the naked eye by detecting and overlaying movement. These systems help us move beyond the capacity of normal-functioning human sensory systems by seamlessly interweaving multimedia information with real-world objects.

Traditional sensory augmentation systems mostly aim to help people scan elements in a situated, physical space, while recent systems increasingly purport to enable people to experience engaging human-computer interaction or enriched intuitions by facilitating engagement with information from both the physical space and virtual information space. Systems for augmenting human sensory capability become more wearable and (Internet-) connected, thereby increasing extraneous workloads in cognition and attention. To address this concern, this paper explores the effects of sensory augmentation on our cognition.

2.3 Sensor-based assessment of user experience

In this paper, we evaluate the effects of sensory augmentation systems on human cognitive processing capability, revealed in sensor data streams. Conventionally, experience sampling methods have participants routinely stop and note down their experiences in real time (right then and there, not later or elsewhere) [34]. The point is for participants to record temporal things like mental effort or feelings while in the moment, relying on their own judgment. In the HCI domain as well, self-reporting approaches (e.g., NASA-TLX or Likert-scales) have also been considered an indicator of user experience during study conditions [4]. These approaches are used *post-hoc* [17, 30]; however, these *post-hoc* subjective approaches are not always reliable. For example, users may self-report a task as having a low task workload even when they struggle with the task, if they believe they did not make any errors [37]. On the other hand, some users may assess an information service as demanding a high workload if the information was served only when they are in an attention-impoverished risky situation, even when the information was actually useful and the cause of the workload was their own error. People are not always reliable at recalling contextual factors that impacted their experience; therefore, relying on subjective memory can be less reliable in an environment where HCI demands or opportunities happen sporadically, and where the quality of user experience depends highly on varying situated, physical contexts.

Ideally, if participants can stop and note each moment of cognitive variation and if we can collect their notes while in the moment, we may be able to track their in-situ experiences at a high rate. However it is difficult to detect appropriate breakpoints in which to probe in-situ user experiences. Transaction level actions (e.g., real-time logs of one's fingertip tapping states) provide insufficient detail about higher-rate cognitive variations [28], which may hold key information about individual differences in cognition and task performance and about factors that differentiate attention-switching strategies and instructional effects between individuals. To overcome these limitations, in the paper we explore sensor-based assessment of attentional states and cognitive load states by using eye-tracking and psycho-physiological measurement, as follows:

Eye-tracking approach Eye movements provide significant insight into a person's thoughts and intentions [43]. In psychology, eye-tracking has been used to understand human cognition by examining visual scan patterns to determine how people acquire and process textural and figural information [21, 52]. In education research, students' eye-tracking measures were examined in order to enable computer tutors to intelligently intervene during learning tasks. Using eye gaze, a computer tutor has detected when a student bypassed instructional objectives or did not read error messages and provided auditory feedback to focus student attention [1]. Indeed, better task performance was achieved by monitoring whether a problem-solver is attending to an on-screen tutor agent and the relevant material and then responding to the student gaze in real time [13]. Advances in accuracy and usability have established this approach as a reliable method to track user's cognitive behaviors [41], such as safe driving behaviors [44], and to evaluate new user interfaces [16, 45]. Eye-tracking approach has been used both as a *post-hoc* assessment tool, and as an on-line diagnostic tool that provides early signs of errors from transaction level data. This suggests that an end-user's eye tracking states may provide crucial information about whether a sensory augmentation system has actually facilitated perceptual performance while not increasing cognitive issues related to dual-task paradigms.

Psycho-physiological approach Eye tracking informs a task-performer's thoughts and intentions, while psycho-physiological signals such as pupil dilation, breathing rate, heart rate variability, and skin conductivity provide insights into a task-performer's affective states [32, 35] and momentary mental workload [14, 17, 33]. This approach is advantageous because physiological responses do not require an overt response by the operator, while at the same time, most cognitive tasks do not require overt behavior [30].

Recently, psycho-physiological measurement has been deemed as a promising approach to developing a personal health system for detecting stress [46], task-performer modeling [10] and task-demand modeling [17]. The psycho-physiological approach has been explored as a tool for online assessment of cognitive load to provide an early forecast of results in conventional *post-hoc* approaches (e.g., task performance based or self-reporting based); however, most studies examined a single sensor data stream to validate its feasibility, such as heart rate variability in a geometry problem solving task [39]; electroencephalography in a training task or in a semantically-complex problem solving task [12, 36]; or pupillary responses in reasoning and searching tasks [20]. The stimuli used in the studies were designed to manipulate participants' mental effort during the task without aiming to affect (or measure) task performance.

Despite its prospects as an on-line tool, prior studies have used a limited number of data streams from which to model aspects of task-performers and also largely overlooked individual differences in psycho-physiological manifestation or cognitive capabilities. A particular sensor data stream that informs us about one performer's state may not work for all (e.g., HR can provide the most indicative set of features for one study participant, but GSR may be more appropriate for another participant, as demonstrated in our prior works; cf. [17, 30]). Thus it is important to examine differences between groups with differing cognitive capability.

This suggests that incorporating as many sensor data streams as possible is perhaps the best route to accurately model users, as envisioned in [48]. For example, Conati and Maclaren (2009) investigated electromyogram (EMG), heart rate (HR), and skin conductance (SC) to detect affective valence and arousal while participating in a number factorization game. The results showed a link between the EMG signal and player emotions associated with a negative valence, but the authors reported technical issues related to HR and SC measurement (e.g., lack of a HR sensor suitable for use with highly active children).

In this context, we explore a hybrid approach that measures multiple channels of psycho-physiological responses and eye tracking states, for assessing the cognitive demands of sensory augmentation for real-world tasks.

3 Proposed sensory augmentation and experimental design

In this paper, we mainly explore two of our human-subject studies, and further discuss the promise of sensory augmentation, which is not included in our prior publications.

The goal of the first study is to investigate the impact of *visual augmentation* on perceptual speed and cognitive processing capability. In our prior study, we proposed a novel display system that provides navigational information with an Augmented Reality (AR) display concept. We evaluated its effectiveness in helping drivers' cognitive mapping between real road views and computer-generated maps on a GPS navigation display [27]. This paper further discusses how AR-incorporated visual augmentation can improve our cognitive processing capability and facilitate attention switching between the virtual information space and the real world.

The goal of the second study is to investigate an impact of *haptic augmentation* on our visual attention management and mental workload. In our prior study, we designed a vibro-tactile cue that provides navigational information as a supplemental modality of conventional audiovisual cues provided by car navigation systems. We examined the effect of its addition on drivers' attention management and psycho-physiological workload. This paper further considers whether vibro-tactile augmentation can complement other sensory cues and reduce unnecessary attentional demand or mental effort.

Here, we summarize the proposed concepts of sensory augmentation and the experimental designs of our human-subject studies.

3.1 Proposed sensory augmentation

Study 1 – visual augmentation by using augmented reality technology In the first study, we prototyped a visually-augmented navigation system. The system displays a computer graphic image of the virtual road over the upper area of the windshield as if it slides down and merges into the real road (See Fig. 2 top). Synchronizing this dynamic visualization with actual car motion was designed to help drivers feel that the virtual information was being seamlessly transformed onto the real roads in their driving context.

We conceptualized a windshield-based head-up-display as a platform that can reduce the driver's divided attention, which is mainly caused by visual and spatial separation between the view of the actual road through the windshield and the secondary navigation display. Also, AR technology has been employed to augment a driver's ability to cognitively synchronize the real-time dynamic images from driving and from the secondary display that are updating in two different orientations and scales. As the result, our display provides a 2.5D representation that can support drivers with both global awareness and local guidance (i.e., integration of 2D virtual map image and 3D AR-incorporated view).

Study 2 – tactile augmentation by using haptics technology In the second study, we built a vibro-tactile steering wheel to present drivers with turn-direction information at intersections [30]. The steering wheel generates a clockwise vibration for the right-turn

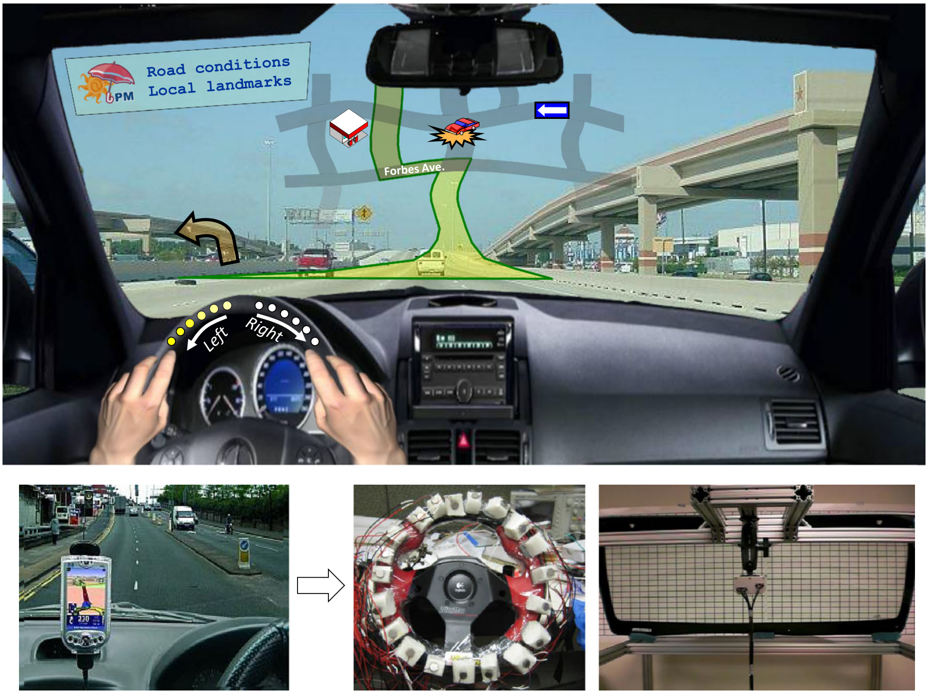


Fig. 2 Proposed sensory augmentation systems: Windshield-based AR navigation display (*top*) and haptically-enhanced steering wheel (*bottom center*) for providing vibro-tactile cues (*top*)

information from 1 to 5 o'clock positions of the wheel and a counterclockwise vibration for the left-turn information from 11 to 7 o'clock. Because drivers physically contact the steering wheel during most of time while driving, we selected it as the vehicular element that can help drivers perceive vibro-tactile information in a natural way. Hands gripping a steering wheel are more sensitive than the back, another body element that can receive vibro-tactile information through the driver's seat.

Twenty motors installed on the front face of the steering wheel create haptic feedback for navigation cues (i.e., the clockwise and the counterclockwise vibration) (See Fig. 2 bottom center). The vibro-tactile cues were designed to intervene along with either voice commands or a visual map, or both. We determined the number of motors, vibration patterns, and memory form as a buffer between motors and the steering wheel through a series of evaluation tests that were conducted with respect to pilot participants prior to the main study.

3.2 Test-bed setup

Test-bed We implemented a three-dimensional driving simulator to conduct usability studies for the proposed sensory augmentation systems. In the simulator, geospatial information from Google Maps for Pittsburgh and Chicago are graphically rendered. Study participants navigate through the simulated cities using a physical steering wheel and foot pedals (See Fig. 3, left).

In the experiments, study participants are prompted through a series of pre-desgined navigation routes. Each route is 3.36 km long and includes 12 intersections that demand

Driver states	Sensor measures
Attention	eyes-off-the-road-time (*s*), eyes-off-the-road frequency (*count*), eyes-off-the-road percent (%), eyes-off-the road time at a glance (*sec/glance*), gaze movement distance (*m*), gaze movement distance per 1-minute driving (*m/min*)
Cognitive load	pupil diameter (*mm*), brink rate (*count/min*), galvanic skin response, heat flux (rate of heart transfer on the skin), heart rate variability, inter-beat (RR) interval, ECG (electrical activity of the heart over time), EEG (electrical activity of the brain)

Fig. 3 Simulated driving test-bed and sensor measure for tracking drivers' in-situ states in attention and cognitive load

turn decisions. During a driving session, participants also encounter 12 light signals, 3 stop signs, and 10 pedestrian crossings. At the pedestrian crossings, drivers encounter either a person pushing a baby carriage or a man wearing a business suit, holding a suitcase, whom they are expected to avoid. If a driver misses a turn, a U-turn must be made to return to the correct route.

Task conditions In the first study, we compared the proposed windshield-based AR navigation display to a regular 2D bird's-eye-view map display installed at the OEM style location (on-screen size: 12 cm × 12 cm). Each driver participated in four unique driving task conditions: AR-based windshield display (ARD) for Chicago and Pittsburgh and regular map-based display (RD) for Chicago and Pittsburgh.

In the second study, we examined the effects of combined sensory feedback in which the proposed haptic steering wheel was partnered with conventional audiovisual modality (i.e., graphic map display and/or voice commands). Therefore participants were presented with a series of sensory combinations such as visual plus auditory (V+A), visual plus haptic (V+H), auditory plus haptic (A+H), and all three forms (V+A+H).

Study participants More than 100 drivers participated in one of the two studies (1.5-hour experiment including 0.5~1 h virtual driving per individual). All participants were shown how to use our test-bed, and how to respond to the traffic events, driving rules and regulations. Participants then performed one round of practice driving.

In both studies, participants were asked to execute all driving tasks in front of two cameras installed at the bottom of the simulation screen in order to capture gaze tracking. Particularly in Study 2, they were additionally instructed to wear body-worn sensor devices such as an ECG-enabled armband (electrocardiography, electrical activity of the heart over time), a wireless EEG headset (electroencephalography, electrical activity of the brain), wireless heart rate monitor belt, another physiological monitor belt, GSR (galvanic skin response) finger sensor during their driving tasks in order to estimate psycho-physiological workload.

In each driving session, participants were given one of the four task conditions as they navigate from the starting position to their destination, navigating through intersections, trying to obey traffic signals and common driving rules (e.g., stay on their own side of the road and avoid the sidewalks). The order of presentation of the task conditions was counter-balanced using a Latin square method. Also, after each test and all the tests, we collected self-reported information from participants (e.g., interviews, Likert-scale questions, and NASA-TLX assessment) and compensated them with $15 (US).

In the analysis we filtered out data from participants who produced erroneous sensor data (e.g., a low quality of eye profile during gaze calibration tasks). Data from 57 participants were analyzed (24 for study 1 and 33 for study 2, respectively [27, 30]). To study individual differences in perceptual and cognitive performance, 28 of the participants were younger adults (*M*=27.5, age range: 19–41), and the other 29 participants were adults over the age of 65 who may be suffering from age-related cognitive decline with normal or corrected-to-normal vision and hearing (*M*=74.0, age range: 65–91).

Measurement For dual-task performance assessment, we collected measures of task completion time, lateral lane deviation, the number of missed turns, traffic signal violations, stop sign violations, and the number of incidents that placed pedestrians in danger. In the interim and *post-hoc* self-reporting sessions, participants were asked to rate their dual-task performance, task workload during each test condition, and preference for sensory augmentation condition experienced.

In the sensor-based assessment, we collected a number of eye-tracking measures and psycho-physiological measures from more than five wearable sensor devices in the form of an armband, chest-belt, headset, or finger-tip worn (See the table in Fig. 3, right). We examined variations in drivers' attentional states while switching eye-fixations between the primary driver view and the secondary navigation display. Drivers' cognitive loads were estimated by tracking variations in statistical features of psycho-physiological responses. The value of selected psycho-physiological features has been demonstrated through our prior work [30].

3.3 Related works – sensory augmentation in automotive applications

Automobile developers have projected dashboard information onto the front windshield using Heads-Up-Display technology (Fig. 4, left – e.g., BMW), which helps drivers check the information with a minimal change of view angle. Without significant modification of the information format, by simply moving the location of the information, the desired results were obtained; however, this format limits the visual field because only a small portion of the front windshield can be used without visual clutter.

Recently, AR technology has been explored in navigation aids prototypes. For example, hidden exits can be represented on a hand-held display (Fig. 4, center top [38]); the route to follow was presented through the windshield as a trolley-cable-like line that appears suspended over the road (Fig. 4, center bottom; Virtual Cable™ navigation - http://www.mvs.net/). These systems help drivers perceive in-situ road shape and determine which roads to follow next (i.e., local guidance); however, all computer graphic images are superimposed parallel with the ground plane in our perspective road view. That is, they provide limited *global awareness* to help drivers maintain awareness of their position relative to their destination or the nearby road network.

Too much audiovisual information in the connected cars can strain human attentional capability, so researchers have explored the use of alternative sensory channels (e.g., touch and tactile sense) to support safe driver-vehicle interaction. In an original study, vibro-tactile output through the steering wheel was evaluated as an effective sensory cue (See Fig. 4 – right bottom, [26]). Though the use of only six epicenters limits the generation of high-resolution vibration patterns, its effectiveness as a navigation aid was demonstrated in multimodal conditions. In another study,

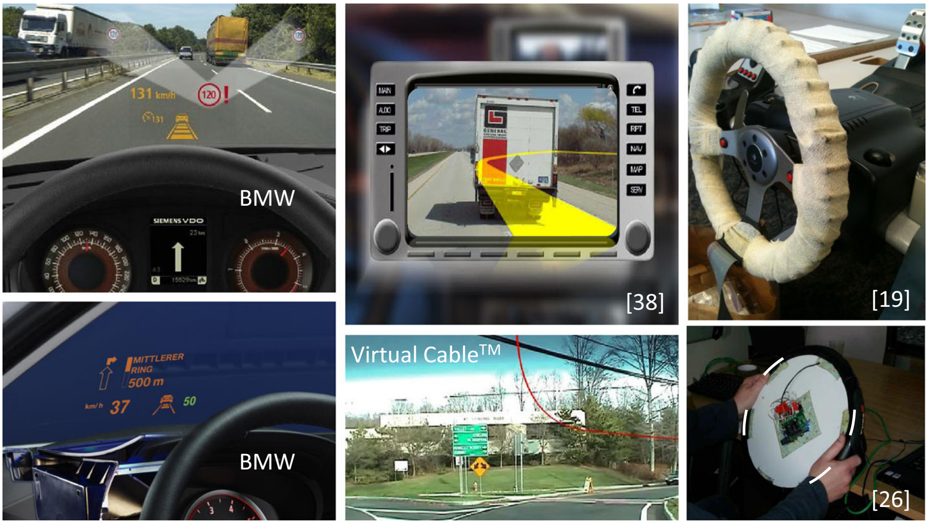


Fig. 4 Augmented Reality and Hpatics in automotive user interface applications

a larger number of actuators (32) were installed on the steering wheel (See Fig. 4 – right top, [19]) to allow for a larger variety of settings of static and dynamic vibration patterns. The study aimed to determine the most effective vibration pattern compared to the use of a visual map as the only baseline, rather than how haptic augmentation can improve our sensory capability by being collaboratively partnered with conventional audiovisual modality.

The driver seat has also been explored as a vehicular element that can deliver haptic cues for some automotive applications (e.g., navigation aid, ringing feedback system for an in-vehicle Blutooth hands-free system, and driver drowsiness warning system [7]). The study revealed that the haptic seat could lead to faster reaction to delivered feedback, and the back support could be superior to haptics in the seat pan position for helping drivers feel aware and perceive the urgency of a haptic warning signal. Although this evaluation focused on the comparison of single modalities (e.g., auditory vs. haptic), which did not include a direct assessment of visual scan states, the study presented transaction-level evidence that haptic augmentation can improve our perceptual capability.

4 Study scope and analysis methods

In our studies, we hypothesize that the proposed sensory augmentation systems will help drivers perform better by reducing divided attention and cognitive load. Informed by cognitive load theory and multiple resource theory [50], we also hypothesize that the benefits from the proposed systems, revealed in sensor data streams, may differ between age groups with different cognitive capability, which will also be influenced by augmentation type (e.g., modality replacement or addition). As a result, we expect to provide important insights for designing sensory augmentation systems that can lead to safer driver-vehicle interaction.

Methods In the *visual augmentation* study, we conducted a two-way ANOVA for the repeated measures of the task performance and eye tracking (‘age group’ as a between-subjects factor × 'display mode (i.e., ARD or RD)' as a within subjects factor) and *post-hoc* contrast tests. In the self-reporting session, we asked participants to rate on a 5-point Likert scale, which display was more helpful for local guidance and for global awareness. On our scale, '1' corresponds to the RD being much better and '5' correspond to the ARD being much better (See Fig. 6).

In the *haptic augmentation* study, we performed one-way repeated measures ANOVA analysis ('age group' as a between-subjects factor and 'sensory augmentation type' as a within-subject factor) and the Bonferroni *post-hoc* test for the measures of the task performance, eye tracking, and NASA-TLX assessment [18]. For the analysis of Likert-scale rating data, Friedman tests and a Wilcoxon Signed Rank *post-hoc* test were conducted.

This paper includes further discussion about self-reported user experience (minimally reported in the prior publication of Study 1 [27]), as well as a re-analysis for the data collected in Study 2 [30]. For Study 2, we will discuss haptic feedback as a replacement or an addition for other sensory modalities, so the combinations, V+H and A+H, are grouped as *sensory replacement* condition (called as *H-replacement* in this paper), and the combination, V+A+H, is renamed as *sensory addition* condition (called as *H-addition*). The audiovisual combination, V+A, is used as the baseline condition as the typical combination of feedback in existing GPS systems, following our previous methodology [30].

5 Findings and discussion

This section includes a brief summary of the main findings in the previous studies and the results of the new analysis. In this paper, our discussion focuses on the effects of sensory augmentation on end-users' attention and cognition under dual-task paradigms.

5.1 Visual augmentation

Main findings in the previous study [27] In the first study, our windshield-based AR display improved driving performance and decreased issues with divided attention across most measures when compared to the typical GPS-based navigation display across all study participants; however, there were significant differences between the two age groups for most of the quantified measures related to task performance (e.g., missed turns, pedestrian in danger, etc.) and eye-tracking (e.g., eyes-off-the-road duration and frequency), as well as self-reported user experience.

As revealed in eye-tracking states, our AR-based system significantly reduced issues of divided attention by facilitating perceptual switching of visual attention between the primary driving view and the secondary information display. Although the results applied to both age groups, the direct effects on dual-task performance were mostly exhibited among elder adults. As shown in Fig. 5, the AR-based approach was mainly helpful for elder drivers to reduce missed turns while improving the response to pedestrians crossing the road.

Additional analysis results Interestingly, specific benefits coming from the reduction of eyes-off-the road issues varied between the age groups. As shown in Fig. 6, for elder drivers, our augmented reality system, ARD, improves awareness of information related to in-situ decision-making (i.e., *local guidance*; See the three bars at the top in the figure). By using our system, elder drivers were able to take advantage of the benefit of the route guidance aids (i.e., proper way-finding without missing turns) while encountering driving and navigation

Fig. 5 The effects of visual augmentation on driver's dual-task performance and visual attention

difficulties when using a conventional navigation display. This implies that costs in attentional and cognitive resources to attend to the secondary virtual information space are mitigated.

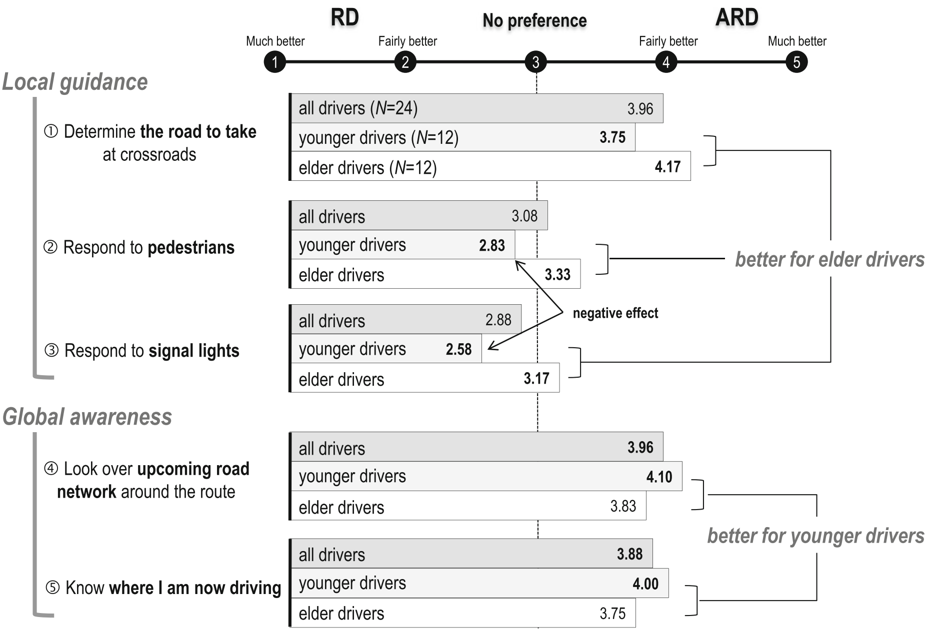


Fig. 6 Self-reported user experience for the aspects of 'local guidance' and 'global awareness'

For younger drivers, the reduced workloads in attention management improved their awareness of the upcoming road network (i.e., *global awareness*; See the two bars at the bottom in Fig. 6). Although our augmented system generally contributed to improved navigation performance, more than the conventional navigation display, it curtailed their perceptual capability in responding to signal lights ahead.

Discussion This study explored '*how to intervene*', an important aspect of cognitive distance (i.e., mental efforts to return to the physical space and apply the extracted information to the task at hand) in Fig. 1. The route and map visuals in both displays heightened driver awareness of driving situations; however, the results showed that even if the same visual information is provided, its representation impacts visual distraction or mental workload differently. Self-assessment results also significantly differed between our demographic populations due to their different cognitive capabilities.

Both navigation displays have attributes that can cause visual interference. Due to the installation position, the conventional display demands that drivers shift visual attention away from the front driving view. Although the augmented display does not have that issue, the graphics projected in this display interfere with other visual information on the road through the front windshield (i.e., overlapping image in the augmented display vs. separate image in the conventional display).

In the evaluation, the overlapped visuals in the augmented display were effective for elder adults to perceive and respond to on-road events, compared to the conventional display. In contrast, for younger drivers the separated visuals in the conventional display were better for that purpose, although the visuals in the augmented display reduced eyes-off-the road issues for younger drivers as well.

These results suggest that people who suffer from cognitive deficits may have more difficulty in reorienting eye fixations among multiple sensory stimuli. Therefore, sensory augmentation systems for these drivers need to minimize the demands for switching overt attention, and should provide explicit auxiliary sensory guidance to help cognitive mapping of physical elements and corresponding visual information. On the other hand, for people who do not have difficulty in splitting attentional resources, cognitive mapping processes can be performed without augmentation, so sensory augmentation systems will need to minimize perceptual interference. Auxiliary information may deteriorate their perceptual performance even though it did not clearly exhibit issues in eye tracking patterns.

Indeed, effective designs and techniques for low-skilled individuals can lose their effectiveness and even have negative consequences for more proficient individuals (called "expertise reversal effect" [24, 25]). When compared to novices (like elder adults who may have been less skilled in dual-task paradigms), experts (like younger adults in our experiment) tend to attend more to relevant aspects of the stimulus, use more heterogeneous task approaches, and use knowledge-based shortcuts.

Expert performance comprises the ability to distinguish relevant from irrelevant information in complex, highly visual stimuli and to draw inferences based upon the perceived information (e.g., [2]). Novices demand minimal extraneous workload in cognitively reorienting and mapping sensory stimuli located in different areas. In geometry problem-solving tasks, for example, by simply integrating formulae with diagrams, learners found it easier to integrate and process both forms of visual information and in turn performed significantly better [5, 6], regardless of intrinsic task complexity. Further, cognitive load theory [5] suggests that the split-attention effect is an important form of extraneous cognitive load that instructional designers should avoid, and is particularly apparent when the same modality (e.g., visual) is used for various types of information within the same display. Therefore, in designing a visual augmentation system it is important to adjust the amount of auxiliary graphics to overlap or to split to be appropriate to one's perceptual skills and experience.

5.2 Haptic augmentation

Main findings in the previous study [30] In the second study, we found that *combining* sensory feedback largely compensated for issues relating to divided attention. Combined with either auditory or haptic feedback, visual feedback (i.e., graphic map) no longer caused older drivers as much difficulty in managing their visual attention (i.e., there were fewer eye fixations switching between the primary driving view and the secondary display view); nevertheless the benefits of sensory augmentation employing the haptic steering wheel (i.e., H-replacement or H-addition) still differed between age groups in attention management and cognitive processing.

As revealed in eye-tracking states, elder adults benefit from multi-modal feedback. Although they still have difficulty using navigation systems (i.e., more missed turns and higher task workloads for the situated dual-task paradigm despite sensory augmentation, compared to younger adults), the metrics related to eyes-off-the-road issues maintained similar levels between both age groups, unlike the results in Study 1. This implies that haptic augmentation systems improve the cognitive processing load of elder adults, rather than visual attention management.

Interestingly, we found that drivers' higher preference for a particular combination and their decreased number of way-finding errors did not always indicate that this combination leads to safer navigation or lower cognitive load. Self-assessment results by younger drivers suggest that the visual map was the most useful feedback, though they preferred the traditional combination of visual plus auditory. Conversely, elder drivers reported that the auditory cues were most useful, but preferred to use all three sensory cues together.

However, when we assessed drivers' eye tracking states and psycho-physiological cognitive load, the results were almost reversed. In general, it was true that when using the full combination of the three sensory cues, drivers showed improved performance in finding their way, with higher driver satisfaction; nevertheless, when using the traditional visual-auditory combination, younger drivers suffered most from divided attention, and the full combination strained the high task workload of elder drivers.

Additional analysis results Indeed, the direct effects of haptic augmentation upon task performance were exhibited among younger adults. As shown in Fig. 7 - lower, the *H-replacement* condition significantly led younger drivers to obey signal lights (d=0.54). The *H-addition* condition also helped them reduce the number of turn misses (d=0.65). There was no such improvement in elderly drivers' dual-task performance.

An interesting finding is that our haptic steering wheel was effective in maintaining a driver's attention on the road; that is, haptic augmentation has reduced the cognitive processing required for visual attention. Simply adding haptic feedback to traditional audiovisual feedback led to more attentive driving by younger drivers (See the bars in the right side of the right-most two pairs in Fig. 7 - lower) who could keep their eyes on the road more by reducing interaction time with a visual map. Drivers could confirm GPS voice commands without necessarily looking at the visual display. Even when drivers missed voice commands from a GPS system due to ambient traffic sound or any other noises, they could obtain still navigation information from haptic feedback. However, for elder drivers the H-addition condition (i.e.,

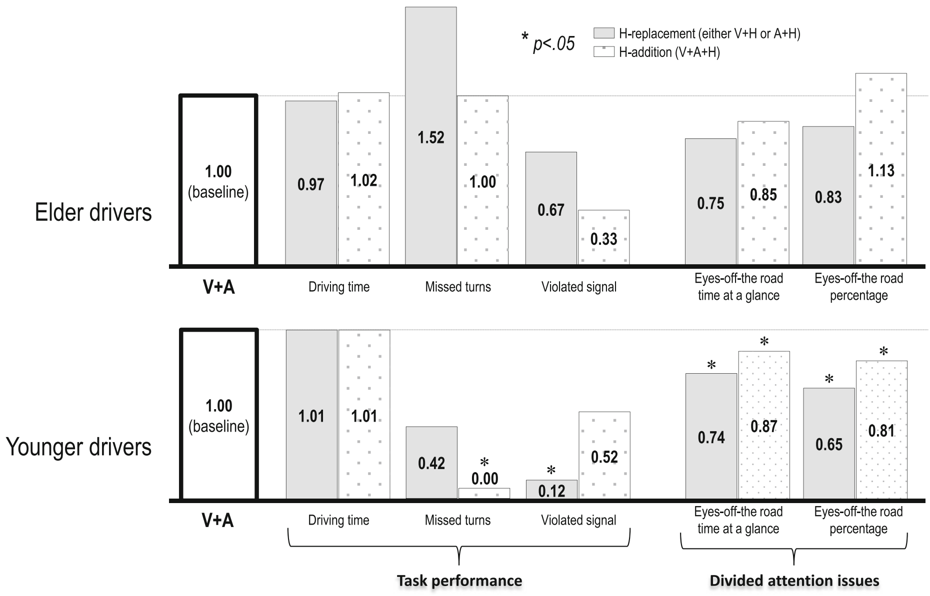


Fig. 7 The effect of haptic augmentation on driver's task performance and visual attention

V+A+H) did not improve attention management. Rather, their psycho-physiological responses demonstrated increased mental workloads [30]. For elder drivers, an H-replacement condition, auditory plus haptic, was safer than using all three modalities.

Discussion In this paper, we have explored how user experience is impacted by sensory augmented systems, and how this differs when a new sensory modality is combined with versus replaced by an existing modality (referred to as an 'intervention type' in this paper). Specifically, we investigated their in-situ interactions with sensor data streams reflecting a user's attention states and mental efforts.

As shown in Table 1, a number of psycho-physiological responses significantly differ with the intervention of sensory augmentation (i.e., *with haptic augmentation* vs. *without haptic augmentation*). As well, many of them highly interacted with specific types of intervention (i.e., *replacement* or *addition*) as well as age groups (i.e., *younger* or *elder adults*).

The intervention types of haptic augmentation significantly impacted participants' attention movement, within each age group as well as across all participants (e.g., vertical eye-gaze movement σ in the left column). Some psychophysiological measures significantly fluctuated by intervention type, as well across each age group, yet the results held across all participants (e.g., blink μ for younger adults and pupil size σ for elder adults in the left column). On the other hand, some measures varied when using any sensory augmentation system, compared with the traditional audiovisual system; however, the measures were not sensitive enough to discriminate the effects of specific types of intervention (e.g., elder adults' blink σ or younger adults' breathing rate σ in the right column).

The results imply that sensor data streams related to overt attention movement (e.g., vertical or horizontal movement of eye fixations) can be practical for estimating the effects of sensory augmentation and specific types of the intervention, without much interference from demographic differences. The results further suggest that individual or demographic differences need to be considered when examining psycho-physiological measures reflecting covert mental effort.

Table 1 Sensor data streams significantly interacted with the intervention of sensory augmentation (sample / 3-sec time-windows; the measures mentioned in the body were highlighted in bold)

	w/o haptic augmentation (i.e., audiovisual only) vs. w/ haptic augmentation, p<.05	
	H-replacement vs. H-addition (p<.05)	H-replacement vs. H-addition (p≥.05, no difference)
Across all participants	**blink** (μ,σ), **vertical eye-gaze movement** (μ, σ), **pupil size** (σ), R-to-R (σ), EEG β_2 (μ), EEG γ_1 (μ), γ_2 (μ)	lateral eye-gaze movement (μ, σ), **GSR** (μ), skin temperature (σ), breathing rate (σ), EEG β_1 (μ)
Younger adults	**blink** (μ,σ), **vertical eye-gaze movement** (μ, σ), **GSR** (μ), skin temperature (μ), EEG amplitude (μ), EEG β_1 (μ)	lateral eye-gaze movement (μ), **breathing rate** (σ), EEG β_2 (μ), EEG γ_2 (μ)
Elder adults	**vertical eye-gaze movement** (σ) **pupil size** (σ), GSR (σ), breathing rate (μ), EEG θ (μ)	**blink** (μ,σ), EEG noise (μ), EEG attention (μ)

For example, the GSR μ measure significantly varied by the factor of intervention type across younger adults; however the results did not hold across all participants even though that measure of elder adults has shown significant differences by the factor of intervention type in the post-hoc *H-replacement* vs. *H-addition* comparison (regardless of the audiovisual condition). This implies that the trend of variations of some psychophysiological responses can be totally reversed between age groups by intervention types of a sensory augmentation system even though those measures were commonly identified as indicative features within each of population group. This provides early evidence that psycho-physiological assessment may promise tracking of expertise reversal effect [24] in a higher sampling rates during interaction with sensor augmentation systems, further detecting the inflection points of the reversal (e.g., changes from 'benefits > costs' to 'costs > benefits' or vice versa).

In addition, the most preferred conditions in the self-assessment (i.e., V+A for younger adults, V+A+H for elder adults) were the worst condition for each age group in terms of attentional states and psycho-physiological task workloads [24]. This implies that the quality of sensory augmentation and user experience cannot be sufficiently detailed relying on conventional measures in task performance or subjective ratings. For the evaluation of sensory augmentation systems, hybrid assessment combining the results of transaction level performance, self-assessment and objective sensor measurement is more appropriate, and usage scenarios should also be conducted in more uncontrolled, naturalistic environment.

6 Conclusions

In this paper, we presented two studies exploring the effects of sensorial augmentation under a dual-task paradigm in an automotive scenario. From a human-computer interaction perspective, we examined how the intervention of multi-sensorial information coming from a virtual information space interacts with user experience and one's cognitive distance.

We demonstrated the effects of sensory augmentation for resolving situational issues related to dual-task paradigms by examining sensor data streams. In addition, we revealed the reversal effect in the pros and cons of sensorial augmentation between demographic populations with different cognitive capabilities. Elder adults who experience cognitive decline suffer extraneous cognitive load imposed by the representation manner of the intervention, compared to younger adults. Superimposing virtual information on the real world can enable them to maintain attention for the real-world primary task, especially when responding to incidental events in physical space; however adding auxiliary modalities in sensory feedback can strain the cognitive capabilities of this population. Therefore, an economized modality combination can work better. On the other hand, for younger adults who may be more proficient in handling dual-task paradigms, the superimposition of virtual information can generate perceptual interference when responding to incidental events in the real-world. Its advantage comes when providing a global overview of the physical and virtual environments. Adding non-visual modalities can lead more attentiveness, without increasing cognitive load.

To summarize, we made three contributions across the two studies. First, we showed how sensory augmentation systems facilitate human cognitive processing capability (i.e., visual attention and cognitive load), especially when users have *interruptive* interventions from a virtual information space while performing a real world task. Second, we discovered early evidence of expertise reversal effects in two demographic populations with different cognitive abilities and then presented implications of these effects, which are specific to each population, to improve the design of sensory augmentation systems. Third, we tested the validity of a sensor-based hybrid assessment method for estimating cognitive distance of end-users in mobile contexts (i.e., effort to shift attention from the physical space to the information space and then effort to return to the physical space and apply the intervened information to the task at hand).

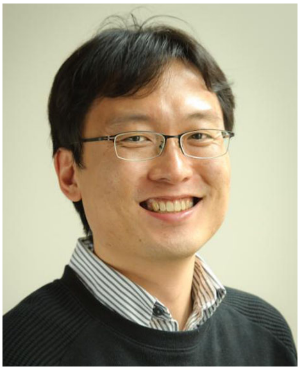
In continuing this work, we have a number of goals. First, our exploration was focused on *proactive* intervention of information (i.e., minimal demand was required to identify the information to extract or interact) and how it has an effect upon our attention and cognition when it is incorporated in sensory augmentation systems. In future work we plan to use our sensor-based approach to decompose the analysis of the effect from each component of cognitive distance (i.e., the first component: physical space → information space and the second component: information space → physical space). By doing so, we can help developers obtain quantifiable implications for identifying which specific parts of interaction schemes or user interfaces of the systems should be focused on; in addition, we will include an exploration of a part of the first component cognitive distance, which is unexplored in this paper (i.e., effort required to identify the appropriate information). Second, in this paper we mainly dealt with the issue of *how to intervene* (i.e., effective representation manners). In the next step, we plan to explore the issues about *when to intervene* (e.g., appropriate interruption timings over continuous time frame) and *what to intervene* (e.g., contextual switching of information to deliver). Third, we will conduct a field study in a more realistic real-world context. For example, we plan to deploy sensor devices in naturalistic driving scenarios in order to monitor in-situ driver and driving states (e.g., by the use of on-board diagnostic and wearable sensor devices) and in-car and on-road situations (e.g., using commercialized black box systems), and then examine when people consciously or subconsciously interact with a virtual information space since those moments may represent moments when there is a reduced cognitive distance allowing them to choose to engage in performing tasks secondary to the primary driving task.

Acknowledgments This project is funded *in part* by General Motors, Carnegie Mellon University's Technologies for Safe and Efficient Transportation, The National USDOT University Transportation Center for Safety (T-SET UTC) which is sponsored by the US Department of Transportation.

References

1. Anderson JR (2002) Spanning seven orders of magnitude: a challenge for cognitive modeling. Cogn Sci 26(1):85–112
2. Canham M, Hegarty M (2010) Effects of knowledge and display design on comprehension of complex graphics. Learn Instr 20(2):155–166
3. Carton A, Dunne LE (2013) Tactile distance feedback for firefighters: design and preliminary evaluation of a sensory augmentation glove. In Proceedings of the 4th Augmented Human International Conference (AH'13). ACM, New York, pp 58–64
4. Cegarra J, Chevalier A (2008) The use of tholos software for combining measures of mental workload: toward theoretical and methodological improvements. Behav Res Methods 40(4):988–1000
5. Chandler P, Sweller J (1991) Cognitive load theory and the format of instruction. Cogn Instr 8(4):293–332
6. Chandler P, Sweller J (1992) The split-attention effect as a factor in the design of instruction. Br J Educ Psychol 62(2):233–246
7. Chang W, Hwang W, Ji YG (2011) Haptic seat interfaces for driver information and warning systems. Int J Hum Comput Interact 27:1119–1132
8. Clive-smith M (2013) Eidos: Audio/Visual Sensory Augmentation. Media Evolution, The Conference Wearable Technology
9. Collins CC (1985) On mobility aids for the blind. In: Warren DH, Strelow ER (eds) Electronic spatial sensing for the blind. Martinus Nijhoff, Boston, pp 35–64
10. Conati C, Maclaren H (2009) Empirically building and evaluating a probabilistic model of user affect. User Model User-Adap Inter 19:267–303
11. Cook AM (1982) Sensory and communication aids. In: Cook AM, Webster JG (eds) Therapeutic Medical Devices: Application and Design. Prentice-Hall, Englewood Cliffs, pp 152–201
12. Coyne JT, Baldwin C, Cole A, Sibley C, Roberts DM (2009) Applying Real Time Physiological Measures of Cognitive Load to Improve Training. HCI 16, of Lecture Notes in Computer Science, vol 5638. Springer, 469–478
13. D'Mello S, Olney A, Williams C, Hays P (2012) Gaze tutor: a gaze-reactive intelligent tutoring system. Int J Hum Comput Stud 70(5):370–389,
    Elsevier
14. De Waard D (1996) The measurement of drivers' mental workload. PhD Thesis, University of Groningen
15. Fisk AD, Derrick WL, Schneider W (1986–87). A methodological assessment and evaluation of dual-task paradigms. Curr Psychol 5(4): 315–327
16. Goldberg JH, Stimson MJ, Lewenstein M, Scott N, Wichansky AM (2002) Eye tracking in web search tasks: design implications, In Proceedings of the 2002 symposium on Eye tracking research & applications (ETRA'02). ACM, New York, pp 51–58
17. Haapalainen E, Kim S, Forlizzi J, Dey A (2010) Psycho-physiological Measures for assessing Cognitive Load. In: Proc. Ubicomp. 301–310
18. Hart SG, Staveland LE (1988) Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. In: Hancock PA, Meshkati N (eds) Human Mental Workload. Amsterdam, North-Holland, pp 139–183
19. Hwang S, Ryu J (2010) The Haptic steering Wheel: Vibro-tactile based navigation for the driving environment. In: IEEE Intl' Conf. PERCOM Workshops. 660–665.
20. Iqbal ST, Zheng XS, Bailey BP (2004) Task evoked pupillary response to mental workload in human-computer interaction. In: Proceedings of the ACM conference on human factors in computing systems. 1477–1480
21. Javal E (1879) Essai sur la Physiologie de la Lecture Annales D'Oculistique
22. Kaczmarek KA (1995) Sensory augmentation and substitution. In: Bronzino JD (ed) CRC handbook of biomedical engineering. CRC Press, Boca Raton, pp 2100–2109
23. Kahneman D (1973) Attention and Effort. Prentice-Hall, Englewood Cliffs
24. Kalyuga S (2007) Expertise reversal effect and its implications for learner-tailored instruction. Educ Psychol Rev 19:509–539
25. Kalyuga S, Rikers R, Pass F (2012) Educational implications of expertise reversal effect in learning and performance of complex cognitive and sensorimotor skills. Educ Psychol Rev 24:313–337
26. Kern D, Marshall P, Hornecker E, Rogers Y, Schmidt A (2009) Enhancing Navigation Information with Tactile Output Embedded into the Steering Wheel. In: Tokuda H, Beigl M, Friday A, Brush AJB, Tobe Y (eds) Pervasive 2009. LNCS, vol 5538. Springer, Heidelberg, pp 42–58
27. Kim S, Dey AK (2009) Simulated Augmented Reality Windshield Display as a Cognitive Mapping Aid for Elder Driver Navigation. In: Proc. CHI. 133–142
28. Kim S, Aleven V, Dey AK (2014) Understanding expert-novice differences in geometry problem-solving tasks: a sensor-based approach, In CHI'14 Extended Abstracts on Human Factors in Computing Systems (CHI EA'14). ACM, New York, pp 1867–1872

29. Kim S, Dey AK, Lee J, Forlizzi J (2011) Usability of car dashboard displays for elder drivers. In: Proc. CHI. 493–502
30. Kim S, Hong J, Li KA, Forlizzi J, Dey AK (2012) Route Guidance Modality for Elder Driver Navigation. Pervasive 12:179–196
31. Klauer SG, Guo F, Simons-Morton BG, Ouimet MC, Lee SE, Dingus TA (2014) Distracted driving and risk of road crashes among novice and experienced drivers. N Engl J Med 370(1):54–59
32. Kort B, Reilly R, Picard RW (2001) An Affective Model of Interplay Between Emotions and Learning: Reengineering educational Pedagogy-Building a Learning Companion. In: Proceedings of International Conference on Advanced Learning Technologies (ICALT 2001), August 2001, Madison, WI
33. Kramer AF (1991) Physiological metrics of mental workload: a review of recent progress. In: Damos DL (ed) Multiple-task performance. Taylor & Francis, London, pp 279–328
34. Larson R, Csikszentmihalyi M (1983) The experience sampling method. New Dir Methodol Soc BehavSci 15:41–56
35. Mauri M, Magagnin V, Cipresso P, Mainardi L, Brown EN, Cerutti S, Villamira M, Barbieri R (2010) Psychophysiological signals associated with affective states. Conf Proc IEEE Eng Med Biol Soc 2010:3563–3566
36. Mercier J, Leger PM, Girard C, Dion JS (2012) Bridging the gap between cognitive neuroscience and education: psychophysiological and behavioral data collection in authentic contexts. Neuroeducation 1(1):5–28
37. Mital A, Govindaraju M (1999) Is it possible to have a single measure for all work? Int J Ind Eng Theory 6:190–195
38. Narzt W, Pomberger G, Ferscha A, Kolb D, Muller R, Wieghardt J, Hortner H, Lindinger C (2006) Augmented reality navigation systems. Univ Access Inf Soc 4(3):177–187
39. Paas FGWC, van Merrienboer JJG (1994) Variability of worked examples and transfer of geometrical problem solving skills: a cognitive load approach. J Educ Psychol 86:122–133
40. Paas F, Renkel A, Sweller J (2004) Cognitive load theory: instructional implications of the interaction between information structures and cognitive architecture. Instr Sci 32:1–8
41. Poole A, Ball LJ, Phillips P (2004) In search of salience: A response time and eye movement analysis of bookmark recognition, In People and Computers XVIII (Proceedings of HCI 2004). Springer, London, pp 363–378
42. Posner MI, Boies SJ (1971) Components of attention. Psychol Rev 78(5):391–408
43. Salvucci DD (1999) Mapping eye movements to cognitive processes (Tech. Rep. No. CMU-CS-99-131). Doctoral Dissertation, Department of Computer Science, Carnegie Mellon University.
44. Salvucci DD (2001) Predicting the effects of in-car interface use on driver performance: an integrated model approach. Int J Hum Comput Stud 55(1):85–107
45. Schiessl M, Duda S, Tholke A, Fischer R (2003) Eye tracking and its application in usability and media research. MMI interaktiv, Vol. 6, available at: useworld.net/ausgaben/3-2003/MMI-Interaktiv0303_SchiesslDudaThoelkeFischer.pdf
46. Setz C, Arnrich B, Schumm J, La Marca R, Tröster G, Ehlert U (2010) Discriminating stress from cognitive load using a wearable EDA device. IEEE Trans Inf Technol Biomed 14(2):410–417
47. Simon HA (1971) Designing organizations for an information rich world. In Computers, Communications, and the Public Interest. 37–72
48. Sottilare R, Graesser A, Hu X, Holden H (2013) Design Recommendations for Intelligent Tutoring Systems: Learner Modeling, vol 1. Army Research Laboratory, Orlando
49. Wickens CD (1981) Processing Resources in Attention, Dual Task Performance, and Workload Assessment Technical Report EPL-81-3/ONR-81-3. University of Illinois, Engineering-Psychology Research Laboratory, Champaign
50. Wickens CD (1984) Processing resources in attention. In: Parasuraman R, Davies R (eds) Varieties of Attention. Academic, New York, pp 63–101
51. Wickens CD (1991) Processing resources and attention. In: Damos DL (ed) Multiple Task Performance. Taylor and Francis, Ltd., Bristol, pp 3–34
52. Yarbus AL (1967) Eye Movements and Vision. Plenum, New York,
Originally published in Russian 1962



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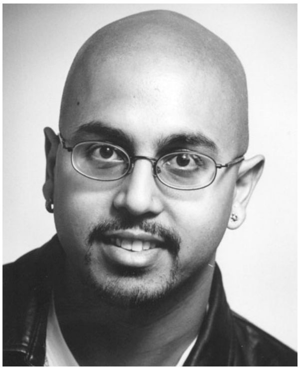

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