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Evaluation of Thermotactile and Vibrotactile Cues to Improve Hazard Perception of Older Pedestrians

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Abstract. The aim of the experiment was to investigate how older people perform a task of hazard perception within different dual-task scenarios when being supported by an assistance system. Baseline performance of 27 subjects aged 60+ was compared to the use of a thermotactile, a vibrotactile and an auditory system. Results indicate that all three systems significantly reduce response time, while only the vibration and the auditory system reduce the number of errors. Error reduction only took place when conducting a visual secondary task, but not with a cognitive secondary task. While workload was reduced by all three systems in the visual task condition, that was not the case with the cognitive task. The vibration system was accepted best by the participants, while the thermal system received the least acceptance. Findings suggest the use of an assistance system using vibration cues to remind older pedestrians of potential hazards in traffic.

Keywords: thermotactile cues, vibrotactile cues, older pedestrians, assistance system, road crossing.

1 Introduction

The aim of the research group FANS was to develop and evaluate an assistance system for older pedestrians. During road crossing, older people have a higher risk of becoming victims of car accidents and suffer more severe consequences than younger age groups. According to German accident statistics [1, 2] 32,602 pedestrians became victims of accidents in 2019. Around a fifth of them, 6,868 were older than 60 years. Together with the age group of 18-25 years old, they were among the most represented group in the pedestrian accidents. Moreover, if considering that frequency of walking as well as distance of walking decreases with age [3], the risk of a person of 80 years to become involved in an accident is 20 times higher compared to the one of a person between 40 and 64 years [4]. Furthermore, older people are more fragile, which increases their risk of dying after a car crash about three times compared to younger people. Of the 417 pedestrians that died in car crashes 235, which is more than half, were older people [1, 2].

When analyzing the reasons for pedestrian caused accidents of older pedestrians, the most prevalent reason accounting for more than half of the cases, is not paying attention to the upcoming traffic [1, 2]. One important cause is the engagement in parallel tasks. Several studies have shown the negative effect of secondary tasks on the crossing behavior of older pedestrians. It has been shown for visual tasks, such as checking the floor for obstacles [5-9], motor tasks, such as walking towards the street while checking for traffic [10, 11], as well as for cognitive tasks such as being involved in a phone call [12-14].

The system that will be developed is supposed to remind the user to refrain from additional tasks (scanning the ground, walking, other cognitive tasks) and to focus attention to the upcoming traffic. Therefore, the system must detect the environment [15], and communicate with the user. Certain requirements are imposed by this specific setting. The system is not supposed to arouse attention from other people and, thereby, expose the user as a person in need of support. Thus, the communication with the user should be as unobtrusive as possible. Moreover, the system does not represent a warning system, but a reminder. Hence, the quality of communication should not be alerting (i.e., very intense) but noticeable, nevertheless. The system should be useable in a normal street environment with cars passing. The ongoing traffic comprises a lot of visual and auditory information, crucial to evaluating the situation and, thus, to safety. The system must not mask any relevant traffic information, meaning visual and auditory cues should be avoided. Another relevant aspect regards costs and comfort. The system must be affordable and not too difficult to put on. Thus, multimodal signals are not a suitable option. Taken together, the most suitable type of communication for the system is the use of tactile cues. This modality tends not to be involved in road crossing otherwise. It is also not particularly alerting by nature and can be transmitted discreetly.

2 Research context and current study

The use of vibrotactile cues in comparison to auditory, visual and different combinations of them has already been studied with younger as well as with older subjects, leading to partly inconsistent results. While Ho et al. [16] found faster responses to auditory compared to tactile cues, the opposite was found in a study from Pitts and Sarter [17]. The authors could also show that, detection rates were lower and response times longer for older compared to younger subjects for visual, auditory and tactile cues. These results are in line with prior research that has shown responses to auditory and visual cues decreasing with age [18-20]. In a follow up study, Huang and Pitts [21] could show that these age differences in response time were only found for visual and auditory, but not for tactile cues.

However, there exists another tactile modality, that has already been used within signaling systems, that is the thermotactile modality [22]. To date the potential of this alternative modality has been investigated by several studies with younger people. Kappers and Plaisier [23] provide a comprehensive review of different studies. Thermotactile stimulation has already been successfully applied in different body regions such as arm, wrist, calf, etc. Its use is recommended for simple communication rather than for complex messages. However, the effectivity and efficiency of thermotactile cues has never been investigated with older people. The current experiment aims to close this gap.

The aim of the current study was to compare two different tactile cues, using a vibrotactile and a thermotactile interface. The two interfaces were developed within the project and tested in a study with older participants. In addition, they were compared to an auditory interface. As described, there are good reasons not to choose auditory cues. However, it is a common way of reminding or alarming people, so it was used as a benchmark. Unlike the reminder system that is developed within the whole project, the system used in the current experiment was an alarm system. While the future system gives signals when pedestrians are approaching a street, independent of the current traffic situation to remind them of a certain behavior, the system used in this experiment is explicitly alarming them of a threat, by giving a signal when a car approaches.

It was investigated, which of the three cue modalities maximizes hazard perception while keeping workload low and being accepted by potential users. Hazard perception was measured in terms of errors and response time from participants age 60+ in a laboratory experiment. Hazard perception without technical support was then compared to hazard perception using the different types of assistance systems. Workload and acceptance were assessed using questionnaires.

Prior research has shown that signal detection improves through the use of cuing systems [17] but results regarding modality effectivity with older participants are inconsistent [21]. Thus, it was expected that hazard detection would benefit from the use of any assistance system. However, whether there would be a difference in modality effectivity was an open question. In a prior study it was found that the visual secondary task impaired the primary task of hazard detection stronger than the cognitive secondary task [9]. Thus, it was expected that participants would benefit more from the system in the visual secondary task condition than in the cognitive. With regard to acceptance, it was expected that participants would prefer the modalities they were more familiar with, i.e., auditory and vibration, over the unfamiliar thermal modality.

3 Development of assistance systems

When sensing any kind of stimulus, one of the first elements of orientation reaction is shifting (visual) attention, often accompanied by turning the head and eyes towards the stimulus [24]. The cues are supposed to make the users look left and right to check for traffic. Thus, the system should cue at the left and at the right side of the body and it should trigger a turn of the head as a reaction to the stimulus. At the same time, the user should not be able to look at the stimulus itself, but direct attention on the street. Therefore, cues were placed near the head such that users were not (easily) able to look at them.

3.1 Components of the thermotactile system

Human skin contains 3-15 times more cold-receptors (6-42 °C) than warm-receptors (30-50°C) [25]. Thus, following a user-centered engineering design approach, “cold” was chosen as stimulus modality. Furthermore, the body contains more thermoreceptors than the extremities [26]. Therefore, the cues were applied to the left and on the right sides of the back of the neck. To cool the skin, we chose Peltier elements (also called TECs – Thermo Electric Coolers), as they have been successfully used for wearable thermal devices before [22]. Heatsinks were applied to the other side of the Peltier elements to conduct away the heat waste produced by the TEC. The size of the TEC was chosen to maximize the amount of skin covered, as thermal stimuli sum up about time and place [27, 25], while being small enough to lay flat. Thermosensors were attached at the inner part (skin-turned) and outer part (turned-away from skin) of the TEC to measure skin temperature as well as warming of the heatsinks. The TECs were integrated into a pair of stretchable suspenders, allowing for individual adjustments. The TECs were connected via cable with a small box attached to the suspenders at participants’ back. The box contained a rechargeable battery as well as the microcontroller that actuated the TECs. The microcontroller was attached via cable to minimize sources of error. However, communication via Bluetooth would have been possible. The microcontroller was triggered by the research software PsychoPy [28] used for the experiment. A person wearing the thermal system is shown in Figure 1.A.

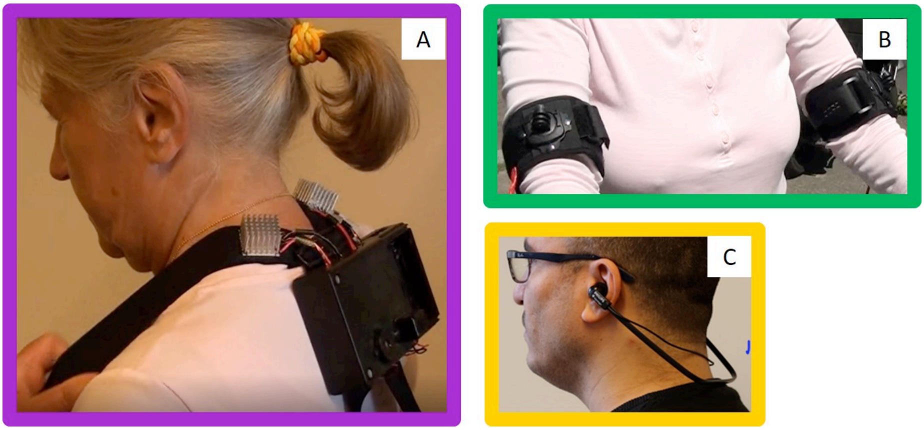


Fig. 1. A. Person wearing the thermotactile support system. B. Person wearing the vibrotactile support system. C. Person wearing the auditory support system.

3.2 Functioning of the thermotactile system

The thermal system measures skin temperature. When an impulse (left or right) is given by the microcontroller, the correspondent Peltier element cools down as fast as possible. Prior research found an accuracy of 96% for direction of change (cold/warm) and suggests a temperature change of 3°C [29]. From research with older people it is known that thermal perception declines with age [30]. Therefore, we chose a target temperature change of 5° C. Because faster temperature changes are detected better [26], we fastened cooling speed up to M=4.4 sec. Once the target temperature is reached, the cooling stops immediately because, as the thermoreceptors adapt quickly [25], there is no additional value in an ongoing temperature stimulation. The system does not aim for a target temperature, as skin temperature changes based on external temperature. Instead the current temperature is measured and reduced by 5°C.

3.3 Safety features of the thermotactile system

Painreceptors are activated at temperatures of 15° C and below, and at temperatures of 45° C and above [31, 25]. Thus, the system was programmed to generate an alarm if one of the parts touching the body went above 42° or below 20° degrees Celsius. The threshold for temperature at the heatsinks was set higher, because it is unlikely that they will be touched. Nevertheless, the system generated an alarm and turned off automatically when the heatsink temperature exceeded 60° C, which is still below the average temperature at which people drink their coffee (63° C) [32]. Additionally, information from the four temperature sensors was displayed online and monitored by the experimenter at all times during the experiment.

3.4 Components and functioning of the vibrotactile system

The vibrotactile cues are applied using fabric vibration cuffs worn at the upper arms. As vibroreceptors change over the course of a lifetime, with Meissner's corpuscles and Merkel cells reducing in number and density with age [33], vibration acuity thresholds are higher for older subjects [34]. Cellphone motors were chosen for vibro-stimulation, as they are commonly used also among older people. The motors used here were button ERMs (electro rotating motors) with a diameter of 12mm, generating an amplitude of more than 1Grms. Vibration motors were integrated in the cuffs and placed at the outside of the arms using Velcro fasteners. Vibration impulses with a duration of 2 seconds are generated by a microcontroller. The current experiment took place in a laboratory with participants sitting at a desk. The mi-crocontroller was triggered by the research software PsychPy [28], like the one used to actuate the thermal system, and was, again, attached via cable to minimize sources of error, but could have been used via Bluetooth as well. A person wearing the vibration cuffs is shown in Figure 1.B.

3.5 Components and functioning of the auditory system

The auditory cues were transmitted via headphones. The volume could be adjusted by the individual, because auditory decline varies across older people [35]. The cues consisted of the word "left" at the left side and the word "right" at the right side. We chose to use words instead of sounds, because hearing loss can be different for the two ears, which may affect directional hearing [36], and sounds could have been misinterpreted more easily. Following design suggestions for older people [36], the words were spoken by a male voice. That is because higher frequencies are lost earlier with increasing age [35], making female voices more difficult to understand. The headphone was directly triggered by the experimental software PsychoPy [28]. A person wearing the headphones is shown in Figure 1.C.

4 Method

4.1 Participants

All procedures were performed in accordance with the Declaration of Helsinki, in compliance with relevant laws and institutional guidelines. Written informed consent was obtained from each participant and privacy rights were observed.

Twenty-seven subjects participated in this experiment. Their age ranged from 61 to 84 with M=73.18 and SD=5.26. Eleven were male and 16 were female. They all had a visual acuity of at least 0.4, measured with Landolt rings. Participants were recruited from the participants data base of the research group FANS of the Technische Universität Berlin, a database of people aged 60 to 90. Subjects received a participation compensation of 12€ per hour.

4.2 Experimental environment and tasks

The pedestrian simulation environment (see Figure 2) had already been used for other studies [9]. This time, participants sat in a distance of 1.2m in front of a 1.5m x 5.8m screen (height x width), projected on the wall by two Acer S1283 HNE projectors with a resolution of 3810 x 1080 pixel. Projection of cars was realized using the open source software PsychoPy [28], the images were created with the program Blender. On a table in front of them was a board with two buttons, green and red, for pressing with the left and right hand, respectively. A joystick was placed below the board that could be used with either hand. The introduction required putting both hands on the board at equal distance below each button. Two loudspeakers were placed at the left and the right side of the table facing the participants. It was chosen to let participants sit, because standing for a long period is very exhausting for (older) participants and the focus of the current experiment was not on motion. However, the use of the assistance system during walking was investigated in a virtual environment as well as within a field study following the current experiment [37].

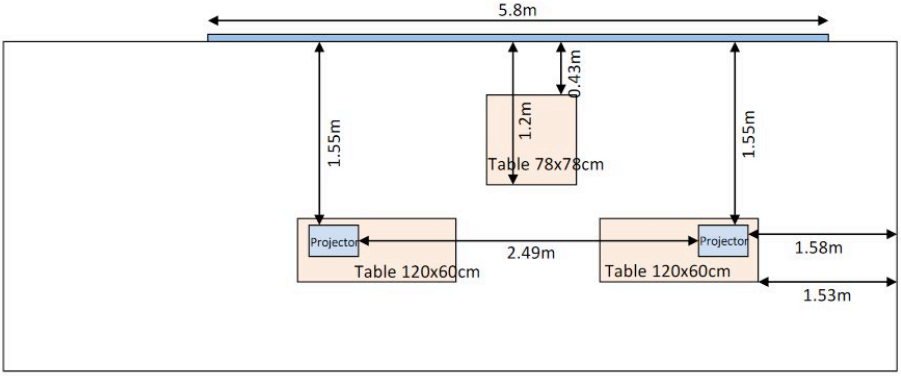


Fig. 2. Schematic representation of experimental setup.

Participants had to carry out two tasks in parallel. The primary task was a hazard detection task. Images of cars appeared on the left or right side of the grey screen at random time intervals. The images were static and cars were either directed towards the center as if they would pass the participants' position (target cars) or directed towards the edge as if they were driving away (distractor cars). A screen shot of the task is presented in Figure 3. Participants could notice the cars using peripheral vision, but had to move their heads to decide whether it was a target or a distractor car. One block consisted of 20 trials with a total of 15 target cars and 3 distractor cars. The task was to pull the joystick when a car was directed towards the center to indicate a "stop" motion. This response modality has been used successfully in a previous study before [9]. Cars were faded in slowly and disappeared either when the participant pulled the joystick or after five seconds, if the joystick was not pulled. Participants were instructed to respond as quickly and accurately as possible.

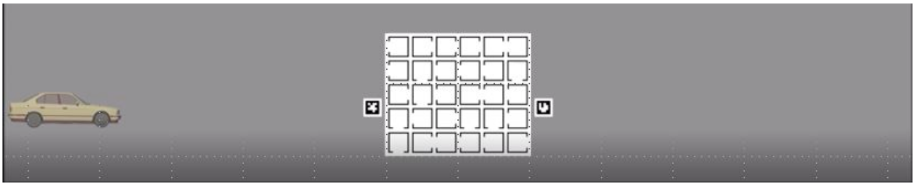


Fig. 3. Screen shot of the visual condition with a target car.

In the experimental blocks, participants used an assistance system with either thermal, vibration or auditory signals to support them with the primary task of hazard detection. The system generated a signal 1-3 seconds (unpredictable) before a target car appeared on the screen. The system worked very well, but not perfectly as it is the case with all real world assistance systems. The current systems generated 10% errors, which were the same for all the modalities: one miss and three false alarms (no car, distractor car, and car at the other side). Two errors occurred per block and error types were balanced across participants, modalities and secondary tasks.

Participants performed the primary task in each block, accompanied by one of the secondary tasks. There were two secondary tasks, one visual and one cognitive. These two tasks were chosen, as visual, cognitive, and motor tasks are the common secondary tasks that compromise older peoples' crossing performance in terms of safety. It is difficult to simulate motor tasks [10] in laboratory settings, and thus, only a visual and a cognitive task were used. These two tasks have already been used successfully in another experiment [9]. The visual search task was displayed in the middle of the screen. It consisted of a 5 x 6 matrix with squares that were open on one of the four sides. Participants had to scan the matrix to check whether it contained a square that was open at the top. In case there was such a target item, they had to press the green button. If there was no such target item, they were instructed to press the red button. After each touch of a button, a new matrix appeared. Participants were instructed to respond as quickly and accurately as possible. The cognitive secondary task was a 1-back memory task. Numbers were read out loud via loudspeakers and participants had to remember and repeat the penultimate number. Participants were instructed to respond as quickly and accurately as possible. The secondary tasks started five seconds before the primary task. Their time structure was unrelated to the one of the primary task.

The experimental software PsychoPy [28] was used to display the tasks, connect the assistance systems, and provide data streams regarding participants' behavior. Data was synchronized and recorded using the Lab Streaming Layer (LSL).

4.3 Design and dependent measures

The experiment consisted of a 5(modality) x 2(secondary task) within-subjects design. With the factor system modality entailing baseline task completion without assistance system (i.e., no modality), task completion using the thermal system, as well as the vibration system, and the auditory system. There were two baselines, one at the beginning and the other one at the end of the experiment to control for effects of learning and fatigue, as had been done in a previous experiment [9]. The secondary tasks were the cognitive task and the visual task.

Response time and errors in the hazard detection task served as objective dependent measures. Response time was defined as the time in seconds between the appearance of a target car and the pulling of the joystick. An error was defined as missing a car, e.g. not pulling the joystick in response to a target car.

Subjectively perceived workload and acceptance of the system served as subjective dependent measures. Workload was assessed using the SEA scale [38]. The scale from 0 to 220 consists of a vertical line with verbal anchors. Participants indicate their level of workload by marking the line at the correspondent height. Acceptance was assessed via eight questions regarding the assistance system and its different modalities. The questions were designed for the current study and are listed in Table 1 in the results section.

4.4 Procedure

After filling in the consent form, participants read the instructions. When everything was understood, they started to train the tasks separately (two minutes each), and as dual-task combinations (two minutes each). If everything went well, the experiment started. The experiment consisted of five system blocks, either of them containing two subsections, a cognitive secondary task block and a visual secondary task block. Each subsection block consisted of 20 trials and had a duration of five minutes.

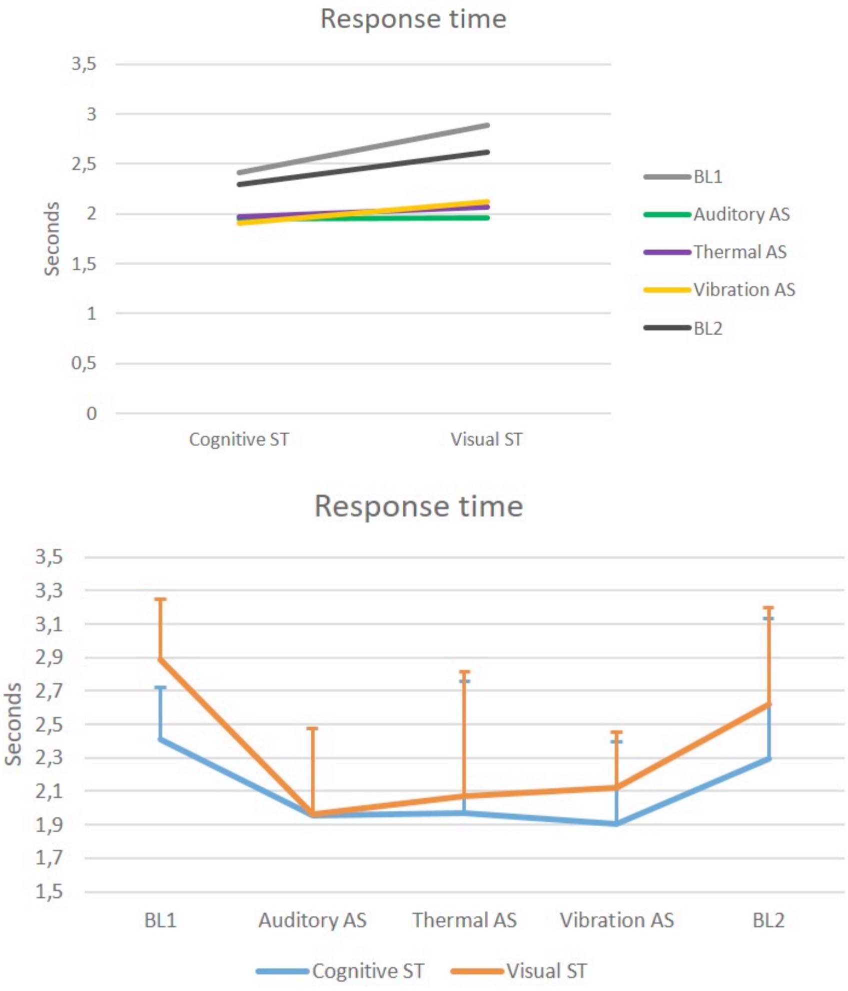
Baseline was measured at the start and at the end of the experiment in block one and five. The three assistance systems were used by the participants in blocks two to four. The order of the three systems was counterbalanced across participants. Whether they started with the cognitive secondary task or the visual secondary tasks was the same for each block within the experiment, but was counterbalanced across participants. Workload questionnaires were given after each subsection (ten times in total). Acceptance questions were posed at the end of the experiment. Finally, a demographic questionnaire was filled in, and subjects were thanked for participation.

5 Results

To analyses the data, ANOVAs for repeated measures with the factors Modality and Secondary Task were conducted. A median split of age was done to group participants into two age groups, and age group served as control variable. Significance of 0.05 was chosen for alpha level. Assumptions of sphericity were tested using the Mauchly-test. In case of violation, Greenhouse-Geisser corrected values are reported. Table 1 gives an overview of the means and standard deviations of the dependent variables for all conditions.

5.1 Response time

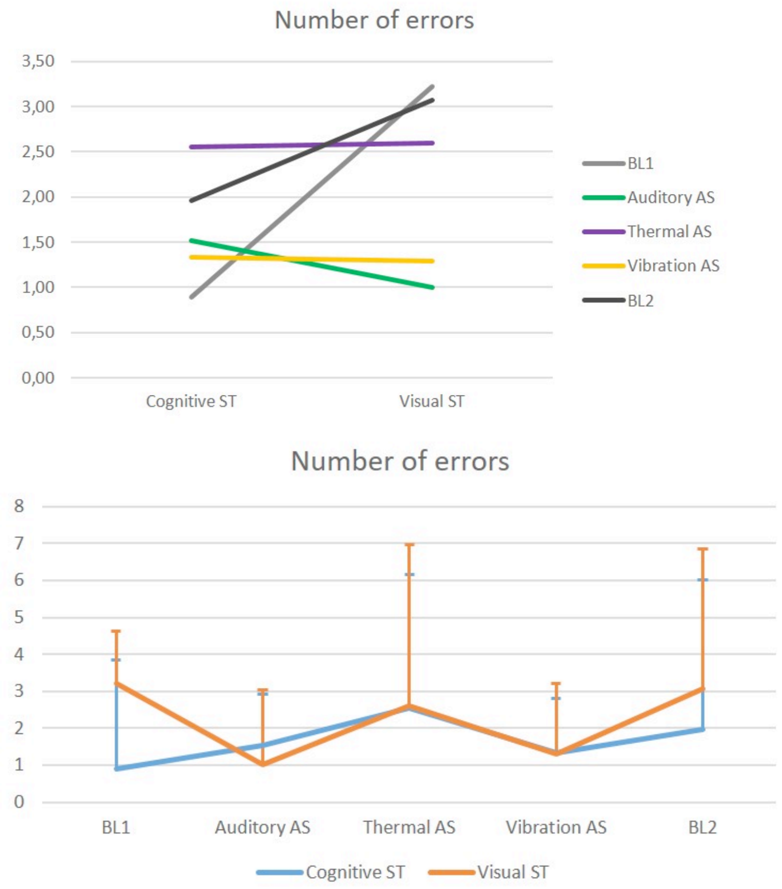
Analysis of response time revealed a significant main effect of Modality, F(1.97, 49.24)=14.37, p<0.001, $\eta^2p=0.37$. Response times without any assistance system were longer (Baseline 1: M=2.65; SD=0.34; Baseline 2: M=2.46, SD=0.71) compared to response time with any of the systems (auditory: M=1.96; SD=0.52; thermal: M=2.02; SD=0.77; vibration: M=2.01; SD=0.42). Comparison of the systems revealed no significant difference between the systems. In addition, the second factor Secondary Task was significant; F(1, 25)=23.46, p=0.001, $\eta^2p=0.48$. Responses to the primary task of hazard detection were faster in the cognitive condition (M=2.11; SD=0.51) compared to the visual condition (M=2.33; SD=0.59). The control variable age group was not significant. The interaction of Modality x Secondary Task was significant, F(2.24, 55.91)=3.11, p=0.05, η^2p= 0.11. Response time was slower in the visual compared to the cognitive condition, with the exaptation of auditory system, where the visual condition was as fast as the cognitive condition. The interaction of Modality x Secondary Task x Age group was marginally significant, F(2.24, 55.91)=2.85, p=0.06, η^2p= 0.09. In the older group the tactile system led to faster responses in the visual than in the cognitive condition. Means are presented in Figures 4a and 4b.



Figs. 4a and **4b**. Means and standard deviations of response time to target cars in the hazard detection task in the baseline conditions, and with the assistance systems of three different modalities (auditory, thermal, vibration) with two different secondary tasks (cognitive and visual).

5.2 Number of errors

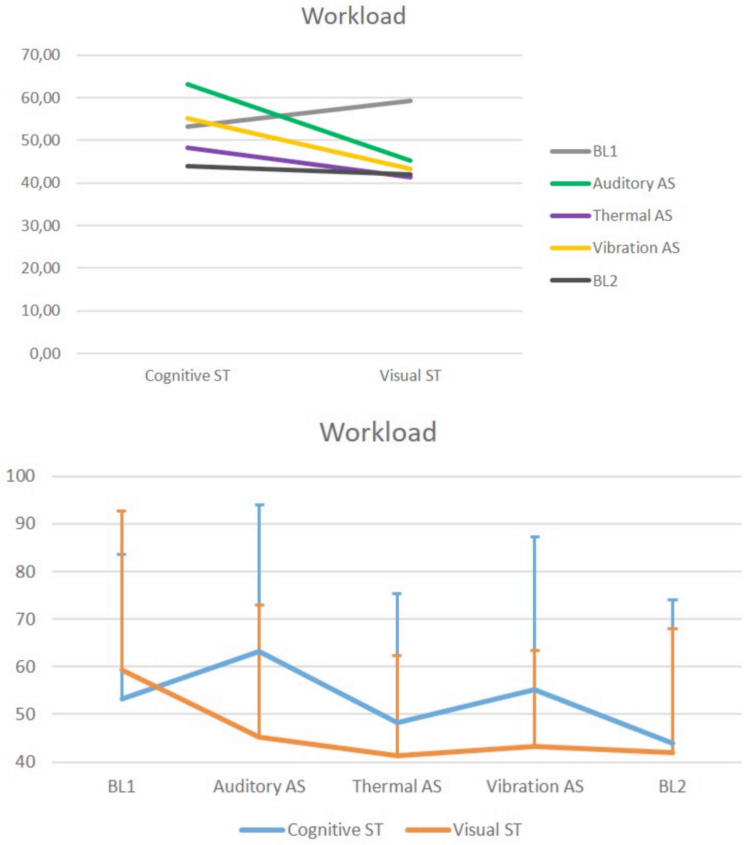
Analysis of errors revealed a marginal significant main effect of Modality, F(2.3, 57.56)=2.86, p=0.06, $\eta^2p=0.10$. Also the main effect of Secondary Task was marginally significant, F(1, 25)=3.47, p=0.07, $\eta^2p=0.12$. Both main effects are further qualified by the significant interaction of Modality x Secondary Task; F(2.67, 66.79)=6.23, p<0.001, $\eta^2p=0.20$. In the visual condition, the auditory (M=1; SD=1.41) and the vibration system (M=1.3; SD=1.46) helped participants to reduce the number of errors to less than a half of the number of errors made in the baseline conditions without the system (baseline 1: M=3.22; SD=2.95; baseline 2: M=3.07; SD=4.05). That was not the case with the thermal system (M=2.59, SD=3.61). This



Figs. 5a and **5b**. Means and standard deviations s of errors in terms of missed target cars in the hazard detection task in the baseline conditions, and with the assistance systems of three different modalities (auditory, thermal, vibration) with two different secondary tasks (cognitive and visual).

reduction of errors could only be found for the visual task but not in the cognitive condition, where the number of errors with the thermal system (M=2.56, SD=4.36) was even higher than the number of errors made in the baseline conditions (baseline 1:M=0.89, SD=1.4; baseline 2: M=1.96, SD=3.77). The number of errors with the auditory system (M=1.52, SD=2.05) and the vibration system (M=1.33, SD=1.92) were lower than the second baseline, but still higher than the first baseline without any system support. Comparison of the systems alone revealed a marginally significant difference between the three assistance systems, F(1.37, 35.53)=3.25, p=0.07, $\eta^2p=0.11$. The control variable age group was also significant, F(1, 25)=5.1, p=0.03, $\eta^2p=0.17$. The older group (M=2.76, SD=3.2) made more errors than the younger group (M=1.29, SD=1.97). None of the other interaction effects was significant. Means are presented in Figures 5a and 5b.

5.3 Workload



Figs 6a and **6b**. Means and standard deviations of workload (on a scale from 0 to 220) in the baseline conditions, and with the assistance systems of three different modalities (auditory, thermal, vibration) with two different secondary tasks (cognitive and visual).

Analysis of workload revealed a significant main effect of Modality, F(4, 100)=3.37, p=0.012, $\eta^2p=0.12$. Comparison of the systems alone revealed a marginally significant difference between the three assistance systems, F(2,52)=2.66, p=0.08, $\eta^2p=0.09$. Workload was highest in the first baseline (M=56.35; SD=31.78) and lowest in the second baseline (M=42.93; SD=28.1). The use of the auditory system led to the highest workload (M=54.15; SD=29.35) of the three systems, the thermal system to the lowest (M=44.73; SD=31.78) and perceived workload with the vibration system was in the middle (M=49.25; SD=26.04). The second factor Secondary Task was only marginally significant; F(4, 100)=5.98, p=0.09, $\eta^2p=0.11$, due to a significant interaction effect of Modality x Secondary Task, F(4, 104)=5.01, p<0.001, $\eta^2p=0.19$. The workload shows the opposite picture of the number of errors. While in the cognitive condition, the auditory (M=63.11, SD=30.81) and the vibration system (M=55.19, SD=32.04) lead to higher workload compared to the baseline conditions without the system (baseline 1: M=53.33, SD=30.25; baseline 2: M=43.85, SD=30.26), only the thermal system (M=48.19, SD=27.13) led to similarly low workload as the baselines. This increase of workload due to the use of assistance systems can only be found for the cognitive task, while in the visual task only the first baseline led to a high evaluation of workload (M=59.37, SD=33.31). When being more used to the task, the three systems (auditory: M=45.19, SD=27.88; vibration: M=43.3, SD=20.04; thermal: M=41.26, SD=21.13) led to similar low values as the second baseline (M=42, SD=25.88). The control variable age group was not significant. The interaction of Modality x Secondary Task x Age group was sig-nificant, F(4, 100)=3.78, p=0.007, $\eta^2p= 0.13$. Both age groups perceived higher work-load in the cognitive task than in the visual task, with the exception of the older group experiencing the visual task as more demanding than the cognitive task in the first baseline. Means are presented in Figures 6a and 6b.

Table 1. Mans and standard deviations of response time, number of errors, and workload for all conditions.

Conditions		Dependent Variables		
		Response time	Number of errors	Workload
Baseline 1	cognitive ST	M=2.4, SD=0.36	M=0.89, SD=1.4	M=53, SD=30
	visual ST	M=2.89, SD=0.31	M=3.22, SD=2.95	M=59, SD=33
Auditory AS	cognitive ST	M=1.95, SD=0.52	M=1.52, SD=2.05	M=63, SD=31
	visual ST	M=1.96, SD=0.52	M=1, SD=1.4	M=45, SD=28
Thermal AS	cognitive ST	M=1.97, SD=0.74	M=2.56, SD=4.63	M=48, SD=27
	visual ST	M=2.07, SD=0.79	M=1.33, SD=3.61	M=41, SD=21
Vibration AS	cognitive ST	M=1.9, SD=0.34	M=1.33, SD=1.92	M=55, SD=32
	visual ST	M=2.12, SD=0.49	M=1.3, SD=1.46	M=43, SD=20
Baseline 2	cognitive ST	M=2.3, SD=0.58	M=1.96, SD=3.77	M=44, SD=30
	visual ST	M=2.62, SD=0.83	M=3.07, SD=4.05	M=42, SD=26

5.4 Acceptance

Frequencies of answers to the acceptance questions are shown in Table 2. Even though all systems generated the same number of errors, at least twelve to 13 participants experienced this differently. Most of them had the impression that the thermal system was generating the most and the vibration system the fewest errors. In line with that, eight and seven subjects stated they perceived the vibration and auditory signals best, while 15 subjects indicated that they perceived the thermal signals less clearly than the others. Consistently, participants experienced the least support from the thermal system (13 subjects). They were more divided regarding the auditory system. Seven participants stated to have had the most support with the auditory system, but seven indicated to have had the least support from the auditory system. Very clear differences emerged when asked to recommend one of the systems to a person in need. Eighteen subjects would recommend the vibration system, four would recommend thermal, four would recommend either of the systems and only one participant would recommend the auditory system. However, when asked which system they would buy for themselves, 18 participants stated they would buy none of the systems.

Table 2. Questions regarding system acceptance and frequencies of answers.

No.	**Answers** **Questions**	Same for all systems/ no preference	Thermal System	Vibration system	Auditory system	none	Results chi-square analysis
1	Number of system errors was highest for which system?	11	9	2	2	n.a.	$\chi^2 = 11$; (3; n=24); p=0.01
2	Number of system errors was lowest for which system?	11	3	7	2	n.a.	$\chi^2 = 8.83$; (3; n=23); p=0.03
3	Signals of which system could you perceive best?	8	2	8	7	n.a.	$\chi^2 = 3.96$; (3; n=25); p=0.27
4	Signals of which system could you perceive worst?	7	15	1	4	n.a.	$\chi^2 = 16.11$; (3; n=27); p=0.001
5	Support with the task was highest with which system?	7	2	10	7	n.a.	$\chi^2 = 5.08$; (3; n=26); p=0.17
6	Support for the task was lowest with which system?	6	13	1	7	n.a.	$\chi^2 = 10.78$; (3; n=27); p=0.01
7	Which of the systems would you recommend to an older person in need of assistance?	4	4	18	1	0	$\chi^2 = 25.89$; (3; n=27); $p<0.001$
8	Which of the systems would you buy?	0	1	6	2	18	$\chi^2 = 23.93$; (4; n=27); $p<0.001$

n.a. – not applicable, means this was not an optional answer for the question.

6 Discussion

The aim of the current study was to evaluate which of two tactile interfaces (thermal vs. vibration) of an assistance system was most suited to support older people in a hazard detection task similar to demands of checking for traffic during road crossing. An auditory interface served as benchmark. During the experiment, participants were involved in a secondary task, as it is often the case in road crossing situations in real life [5-8]. Effectivity in the hazard detection task during secondary task completion was assessed by analysing response times and errors. Workload was measured to control whether the system imposed additional load on the users, and acceptance towards the different modalities was assessed for a better understanding of subjective attitude towards the different modalities.

6.1 Response time and errors in the hazard detection task

Overall, in line with the first hypothesis and prior studies [20], the systems improved responses to hazards, as they led to a significant decrease in response time, independent of the modality. The responses were faster when conducting the cog-nitive task in parallel compared to the visual task. This finding confirmed the second hypothesis and was expected as in a prior study performance in hazard perception had suffered stronger from the visual than from the cognitive secondary task [9]. There was only one exception, when using the auditory system, responses in the visual condition were as fast as in the cognitive condition.

It was found that the vibration system as well as the auditory system were able to re-duce errors to less than half, compared to the baselines. However, this effect took place only in the visual condition. The thermal system, however, failed to improve performance regarding accuracy in terms of error reduction. Thus, with regard to errors, the first and second hypotheses were confirmed only partial. The systems did not work perfectly and conducted two errors per block/secondary task. While participants working with the vibration and the auditory system, they had error rates below that level (<1.5), working with the thermal system resulted in higher error rates (>2.5). While there was no difference of age group with regard to response time, the older group conducted more errors than the younger. However, this effect did not interact with the use of assistance system.

6.2 Workload

Workload was higher in the first compared to the last baseline, and higher in the cognitive compared to the visual condition. In the visual condition the workload with the systems was lower than the first bassline and similar to the second one. In the cognitive condition only the thermal system was able to reduce workload below the first baseline. The vibration system led to a workload similar to it and the auditory system even increased the workload to a level above the one of the first baseline. Workload with all three systems was higher than the level found for the second baseline.

The high workload resulting from the combination of auditory system and cognitive secondary task, which was presented auditory as well, may be due to this overlap in source of input modality. So, it is probably not (only) the cognitive load, interfering with the auditory signal, but the auditory inputs interfering with each other. However, in natural road crossing there is a lot of important auditory information at the same time as well. This is why we refrained from the auditory modality on a theoretical level. This high perceived workload supports the assumption that auditory signals are not the right choice for this type of assistance system being operated in a noisy environment.

An alternative explanation for the stronger interference of the auditory system with the cognitive task on the level of perceived workload is the use of speech instead of sounds. It is possible that the working memory resources requested for the processing of speech may have interfered with the resources requested for memorizing the numbers. However, if anything, this is another argument against the use of auditory signals in dual-task settings and noisy environments.

Workload decreased from first to second baseline, while the response times and the error rates stayed the same or even increased. This indicates that subjective perception does not depend on the objective performance.

6.3 Acceptance

Overall, the vibration system was most accepted by the participants. They indicated to perceive the signals well, which even led to the impression of fewer errors composed by the system. Consequently, they stated to have been supported the best by the vibration system. And last, even though most of the participants would not buy such a system to support themselves (because they did not yet feel the need for such an assistance), most of them would recommend a vibration system to an older person in need of support with road crossing. The thermal system received the least acceptance by participants. Thermal signals were perceived less clearly than the others, such that the thermal system was perceived as committing more errors and providing less support. Nonetheless, four participants would recommend a thermal system to an older person in need of assistance. Impression of the auditory system was rather mixed. This is represented best by the same amount of participants indicating to have had the best as well as the fewest support from the auditory system. Only one person would recommend the auditory system to others. It was expected that the auditory and the vibrotactile system were rated better than the thermal system. This hypothesis was partially supported, as the vibration was rated best and the thermal system was rated lowest. Ratings of the auditory system were lower than expected.

6.4 Limitations

The use of different modalities is to some extend confounded with the placement of the interface. While auditory information can be perceived through space, tactile information can only be perceived when it is applied directly to the skin (or very close to it). The exact positioning on the skin can have an impact on the quality of perception. In this study we compared vibrotactile signals applied at the upper arm and thermotactile signals applied at the back of the neck. We chose this positions in order to maximize perception. However, to understand what would be the optimal position of the two actuators on the skin of an older person, especially for the thermotactile modality, more basic research is needed.

As the high standard deviations suggest, individual differences with regard to errors with the systems are very high. For each modality there was at least one participant completely underperforming, while not having problems with the other two modalities. This is in line with general findings regarding the age-related decline of perceptual and cognitive abilities. It often shows that decline in one area is unrelated to decline in another [35]. This result is a strong argument for the use of multimodal cues in assistance systems designed for older people, to allow for compensation of the modalities that are already perceived worse.

6.4 Interface modalities

We assume that the reason the thermal system was able to improve response time, but at the same time did not sufficiently reduce the number of errors, is the nature of stimulus. In the acceptance questionnaire, more than half of the participants indicated to have perceived the thermal signals as weaker than the other two. In line with this, the thermal system imposed less additional workload than the other two. When detected, the stimulus led participants to comply with the system, turn their heads and respond to the potential hazard, independently of system modality. Therefore, they were faster when using any of the systems than they were without system support. However, as the thermal signals seemed to have been rather subtle compared to the other two, participants missed a few of them. Consequently, they missed the corresponding potential hazards. The mean error rate with the thermal system was 2.5, which is 12.5 percent (of the 20 trials per block). Thus, error rate with the thermal system was more than four times higher compared to the error rate (<4 percent) of temperature change found by Wilson et al. [29]. Moreover, in the cognitive condition, participants made more errors using the thermal system compared to the baseline. This is likely an indicator for complacency [39], meaning that overly relying on a technical system can in fact reduce safety. If older pedestrians fully rely on the system to inform them about any approaching car, a signal that is too subtle, such as the thermal signals, may cause truly dangerous situations.

As prior studies have shown, perception of thermal signals is vulnerable to certain external factors, such as humidity and temperature [40], as well as to factors related to the persons' self-perception within the environment, such as sitting down versus walking [29], or the body position of the thermal stimuli [23]. Results of our experiment are in line with this prior research, as some stimuli were missed by participants and overall acceptance was low. Nonetheless, specific features, such as distinguishing cold from hot signals are very well executed by the majority of people [41], and discrimination of different other qualities of thermal signals, such as temperature difference and velocity of change, can be learned by people in a short amount of time [42]. Together with the low workload they impose compared to other modalities, they seem well suited for situations that require graceful interruptions [22], and further research may lead to more promising results. However, for the use by older people in safety related environments, we do not recommend systems communicating via thermal signals. These can easily be missed by people, and put them in danger.

In contrast, the perception of auditory stimuli was not impaired, presumably because we followed design recommendations for older users [36]. The advantage of using auditory systems is that they are easily adaptable to individual abilities as well as personal preferences. However, we do not recommend the use of auditory assistance systems in environments that contain safety relevant auditory information. In fact, the auditory system was chosen as a benchmark, to make sure the more unconventional tactile systems were not outperformed in terms of effectivity and efficiency.

The vibration system not only performed as good as the auditory system, and was better than the thermal system, but was also more accepted by users than the conventional auditory system. Even though vibration perception changes with age [34], the current experiment shows, in line with prior studies e.g. [21], that sufficiently intense vibration signals are a reliable method to alert older people.

Moreover, in the current experiment it was shown that hazard detection can be significantly improved through the use of vibrotactile cues. Thus, it is concluded that vibration signals are the most promising option for an assistance system for older pedestrians.

6.5 Conclusion

The current study aimed to provide further insight into the use of vibrotactile cues by older subjects. Moreover, it was the first experiment investigating the use of thermotactile cues by older people. Findings are encouraging, because results indicate a general advantage through the use of tactile cues by older people, despite age-related reduction of sensitivity. While thermotactile cues are more likely to remain unnoted and therefore incorporate a potential risk of overconfidence, vibrotactile cues result as a very promising modality for subtle communication with older subjects.

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