Where to turn my car? Comparison of a Tactile Display and a Conventional Car Navigation System under High Load Condition

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ABSTRACT

Tactile displays are an actively studied means to convey large amount of spatial information in the car. Their advantage compared to conventional car navigation systems is their ability to free the driver's visual and auditory senses. Previously the tactile displays were integrated into the seat of a car to present multiple direction information to the driver. However, in the commercial cars the seat is used to provide the vibro-tactile warning signals, so driver might not differentiate between navigation and warning information. Furthermore, the amount of information presented with tactile displays can cause significant cognitive workload, performance degradation and distraction to the driver. In this paper, we explore different methods of encoding multiple directions information with a tactile belt in the car. We compare the vibro-tactile presentation of spatial turn-by-turn information with a conventional car navigation system to measure cognitive workload, performance and distraction of the driver. We found that drivers showed better orientation performance on the tactile display than with the conventional car navigation system. At the same time there was no difference in cognitive workload, performance, and distraction. Thus, a tactile interface can be useful to present more information than simple left or right directions in high load driving conditions in which drivers are required to observe the traffic situation with their visual and auditory senses.

Categories and Subject Descriptors

H.5.2 [**User Interfaces**]: Haptic I/O; 1.3.6 [**Methodology and Techniques**]: Interaction techniques

General Terms

Human Factors, Experimentation

Keywords

Car navigation system, Tactile interface, Cognitive workload

AutomotiveUI'10 November 11-12, 2010, Pittsburgh, Pennsylvania
ACM 978-1-4503-0437-5

1. INTRODUCTION AND MOTIVATION

In the recent years a considerably increase in the demand of the car navigation systems has been witnessed. In 2008, the world's total shipment of car navigation devices was over 70 million units[1], which is higher than the production rate of cars around 52 million[2] in the world. The modern car navigation system provides many services other than its basic functionality of providing route information [16] to the driver. The complexity of the car navigation systems is increasing day-by-day, but the channels of communication used today remain mainly limited to visual and auditory user interfaces. These limitations are likely to increase the drivers' mental workload [14]. The mental workload is directly related to the capacity of an operator spent on his or her task performance [10]. The driver deals with information in the car via the available communication channels and in a complex situation this may cause major decline in the performance, increase the cognitive workload, and can also cause distraction and sometimes even accidents. According to the Multiple Resource Theory (MRT) [19], multiple tasks performed on the same component of a channel can result in excessive workload. Thus, the mental workload of the driver can be decreased by providing an additional channel of communication in car navigation systems.

Most of the car navigation systems rely on turn-by-turn guidance displays [12]. Though direction information would be sufficient to reach a turn, distance presentation can be helpful in some cases while driving a car [18]. In this paper we present the joint presentation of both turn-by-turn direction and distance information to the driver by means of a tactile display.

Tactile displays in the form of a tactile seat have already been used in previous studies like [11] to present eight different directions to the driver of a car. In the first study presented in this paper we explore the methods of encoding multiple directions with a tactile belt. In our previous work, we showed that multiple distances can be successfully presented with a tactile display to a driver while approaching an upcoming crossing [1]. However, multiple directions and distances increase the complexity of the information in a driving situation. This might impose excessive cognitive workload, cause distraction, and decrease the performance of the driver. Though the conventional car navigation systems successfully provide the multiple directions and distance information but attract the visual and acoustic attention of the drivers. Therefore, we designed a study to compare the tactile interface with the conventional car

[1] http://www.reportlinker.com/p0138518/Global-and-China-Car-Navigation-Industry-Report-2009-2010.html
[2] http://www.worldometers.info/cars/

navigation system (visual and auditory displays). The effect of a tactile display on the cognitive workload and performance of the driver was compared with a visual display in a car simulator environment by van Erp and van Veen [8]. Workload and performance, however, have not been explored in an urban scenario where various real-time factors (e.g., a spontaneous decision to avoid a bicyclist who suddenly appears in front of the car) could affect the workload, distraction, and performance of a driver. In this work, we aim to compare a tactile display to a conventional car navigation system with respect to the cognitive workload, distractions, and performance in a real urban scenario.

The remainder of this paper is organized as follows. In Section 2, the related work in the field of spatial information encoding in automobiles is discussed. Section 3 describes the direction and distance encodings with our tactile interface followed by Section 4 explaining our pilot study to explore direction encoding. In Section 5, we provide the details of our experimental evaluation and Section 6 presents the results. We conclude the paper with a summarization and a discussion of the outcomes of our study.

2. RELATED WORK

The multiple resource model [20] proved to be effective in time sharing efficiency. Especially in such conditions, when multiple tasks imposed but the model is still challenged by the issue of adding another level to the modalities dimension related to the tactile interface. In the following we discussed the previous work addressing the vibro-tactile encodings in the automobiles and their limitations.

Tactile interfaces are actively scientifically studied as a display of the car navigation systems [1, 11]. Usually the drivers need to know the distance to a calculated crossing and the direction where to take turn for successful navigation [18]. de Vries et al. [7] designed a car seat fitted with an 8x8 matrix for vibrators and used it to code eight different directions. The results showed that tactile displays provide the favorable means of presenting directional information. Tactile interfaces have been effectively used in Advanced Driver Assistance Systems (ADAS) on commercial scale e.g. by Citroën[3] and Audi[4] in the seat and steering wheel, respectively. Thus, there is a need to investigate that multiple directions can be presented with a tactile display when it is embedded into other parts of a car, e.g. a seatbelt so drivers will be able to differentiate navigation signals from warning signals. Hogema et al. [11] evaluated the performance of the design of de Vries et al. on five types of real road conditions. The results of the field study showed that the ability of drivers to localize tactile cues is nearly perfect. The results of previous studies encouraged the encoding of the tactile display for multiple direction encoding. Distance information is presented by van Erp and van Veen [17] with vibrocon (vibro-tactile icon) for conveying distance according to three different classes (250 m, 150 m, and 50 m). The results showed that vibrocons reduced the visual burden of the drivers. In previous studies [1, 7] we observed the increased level of the complexity of spatial information to be presented with the tactile display. The complexity of the information to be presented with the tactile displayed could need more attention of the drivers which can affect their performance on other secondary tasks. We are required to investigate the effect of performing a secondary task on the drivers' cognitive workload performance, and distraction while dealing with the vibro-tactile information. van Erp and van Veen [8] compared a tactile display with a visual display in a car simulator. The results showed that the tactile display reduces the cognitive workload of drivers compared to visual display especially in a high work load conditions. Performing a multiple number of tasks at a time constraints on the human cognitive architecture [6] The cognitive workload of drivers can be investigated by analyzing their performance on a secondary task.

Paced Auditory Serial Addition Task (PASAT) is a frequently used secondary task in the context of driving [3]. PASAT is a cognitive task to measure the working memory, speed of information processing, and sustained and divided attention [4]. PASAT was originally proposed to measured change in the performance of patient during recovery of closed-head injuries [4]. Balzano et al. instructed a group of multiple sclerosis patients and a control group of healthy people to perform a counting task: A series of pairs of numbers had to be added at a rate of 3 and 2 seconds respectively. The results showed that both groups of the participants performed significantly better on the 3 seconds task as compared to the 2 seconds task. No significant difference was found between groups on late responses to the task. The heart rate and blood pressure are the primary measures of human workload and stress level [2]. In our study we need to make a highly workload environment by introducing a demanding secondary task. Mathias et al. [13] discovered that the heart rate and blood pressure was significantly high during testing periods of PASAT. So, PASAT can be qualified as a non-visual secondary task for further evaluations.

Previous studies did not address the effect of the increasing amount of spatial information to be presented with the vibro-tactile signals combined with the all factors of primary task of driving on the cognitive workload, performance and distraction of the driver on other tasks. In our study we will investigate the limitations of the previous studies [8, 7].

3. PRESENTING SPATIAL INFORMATION WITH A TACTILE DISPLAY

In this study we use a tactile belt to provide turn-by-turn information to the drivers. Figure 1 depicts an example of the vibro-tactile cues that are conveyed to the driver while approaching a crossing.

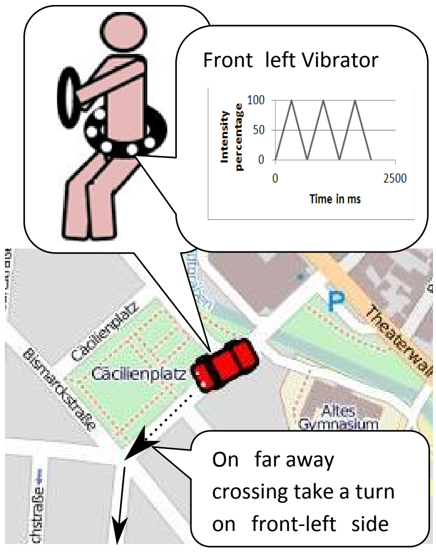

Figure 1: Three pulses of the vibro-tactile signal on "front-left" side of the tactile belt indicate that the car is approaching the calculated crossing after covering the "far" distance.

[3]http://www.citroen.com.hk/tech/sec_04.htm
[4]www.audiworld.com/news/05/naias/aaqc/content5.shtml

In order to present the direction *front-left* a front-left vibrator of the tactile belt will trigger on the respective side. The front-left vibrator of the tactile belt will trigger four times before the crossing to present four categories of distances as proposed by Fukuda et al. [9]: (1) Very-far, (2) Far, (3) Near, and (4) Turn-now. The vibro-tactile signals for *very-far* and *far* help the driver to prepare for the crossing. Furthermore, the *near* signal can help the driver to take the intended lane or turn-on the indicator. Finally, the vibro-tactile signal for *turn-now* indicates that the driver has to take a turn immediately.

In this section the design of vibro-tactile encodings for presenting these multiple directions and distances to the drivers is described. In the remainder of the paper we use the term *tactile spatial display* to refer to the presentation of multiple directions in combination with multiple distances with our tactile display.

3.1 The tactile display

In previous studies [17, 11] the tactile display appears to be a valuable alternative to provide information in automobiles. The choice of a *tactile spatial display* is motivated by the fact that conveying navigation information with the tactile display proved to be very efficient [11, 17]. The drivers perceived the tactile messages called "tactons" successfully [11].

Our tactile belt is built to be worn around the waist of the driver. It is made-up of the eight vibrating components called "vibrators". The vibrators are sewed in the fixed circumference of 90 cm long fabric tube and are spread around the waist of the driver and allow stimuli in respective directions. The driver can perceive the vibro-tactile signals while seated in the car.

3.2 Displaying multiple directions and distances

The information regarding the direction and distance of the next turn are important to present the turn-by-turn information in the automobiles [18]. As discussed by Brewster et al [5], the tactile parameters qualified for vibro-tactile information encoding are frequency, amplitude, waveform, duration, rhythm, and body location. In our previous studies [1] the *rhythm and duration based distance encoding* was the most successful method of encoding distance with the tactile belt. In the *rhythm and duration based distance encoding* the parameters of rhythm and duration are modified in order to design tactons. Vibro-tactile signals feel like countable pulses. The driver counts a number of pulses to interpret the category of distance. The four categories of distances "very-far" (i.e. 200 to 150 meters), "far" (i.e. 100 to 80 meters), "near" (i.e. 50 to 30 meters) and "turn-now" (i.e. 10 meters) are presented with the tactile display by altering the duration and amount of pulses: The distance "very-far" is presented with 4 pulses in 2.5 seconds. The distance "far" is presented with 3 pulses in 2 seconds. The distance "near" is presented with 2 pulses in 1.5 seconds. The distance "turn-now" is presented with 1 pulse in 1 second.

Directions can be divided into the cardinal directions and ordinal directions [7]. de Vries et al. [7] showed that the drivers can distinguish eight different levels of directions with the tactile display. In this study we encode four different levels of directions (left, front-left, right, front-right). We consider four levels of directions for vibro-tactile encoding due to the fact that they frequently occur in a realistic urban scenario.

The body location is best suited to present direction information [7, 11] among tactile parameters [5]. In our study we compared four types of encodings to present the direction information: (1) *one vibrator design*, (2) *one vibrator with distance design*, (3) *two vibrators front design*, (4) *two vibrators side design*. de Vries et al. [7] proposed a bar and block design with the tactile seat to present direction information to the driver. In the block and bar design "front-left" and "front-right" directions are presented by activating 9 vibrators on the front-left and the front-right side of the seat respectively. In the bar design 24 vibrators on the left and right side of the tactile seat are activated to convey "left" and "right" directions. In the block design the "left" and "right" direction are presented by activating 6 vibrators on the left and right side of the seat respectively. In order to present direction information, the vibrators of the seat are activated with inter-stimulus intervals of 125, 250, and 500 Milliseconds. In our study we encoded the block design of de Vries et al. [7] with the tactile belt by activating one vibrator on respective side depicted in Figure 2 and used the term *one vibrator design* for the encoding. The advantage of our design is that it utilizes only one vibrator to present direction as compared to multiple vibrators in the block design. We used the term *one vibrator with distance design* the *one vibrator design* combined with *rhythm and duration based distance encoding* [1]. In *two vibrators front design* the front and front-left vibrators are activated to present "front-left" direction as depicted in Figure 3. The left vibrator of the tactile belt is activated to present "left" direction. In *two vibrator side design* the left and front-left vibrators of the tactile belt are activated to show "front-left" direction as shown in Figure 4. In order to present distance information with the *two vibrators front design* and *two vibrator side design*, we used *rhythm and duration based distance encoding*.

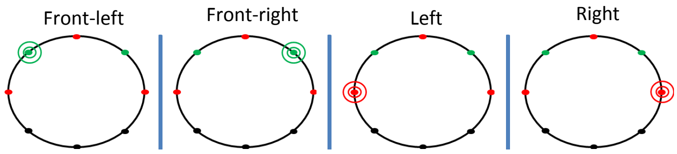

Figure 2: One vibrator design: One vibrator on a particular side is activated to present the respective direction

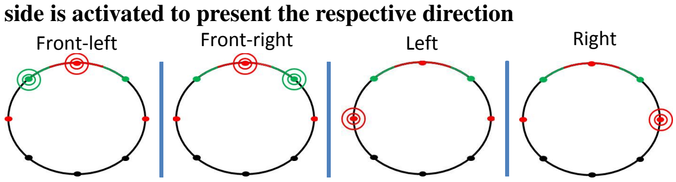

Figure 3: Two vibrators front design: The front-left or front-right vibrator is activated to present a particular direction.

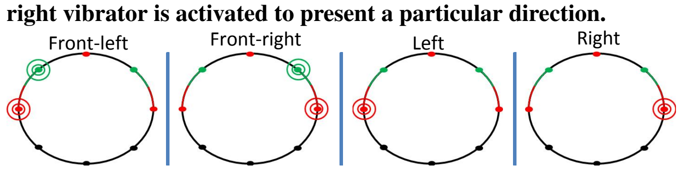

Figure 4: Two vibrators side design: The left and front-left vibrators or the right and front-right vibrators are activated to present a particular direction.

4. PILOT STUDY

The objective of our pilot study is to determine an appropriate vibro-tactile direction encoding with our tactile belt for further evaluations. We evaluated *one vibrator design*, *one vibrator with distance design*, *two vibrators front design*, and *two vibrators side design*. The pilot study investigates the specified questions:

1. Does the presentation of distances with direction help to decrease the error in interpreting the information?

2. Which vibro-tactile information design among *one vibrator design*, *one vibrator with distance design*, *two vibrators front design*, and *two vibrators side design* is more helpful for driver to achieve the best performance?

4.1 Participants and apparatus

We recruited 3 male participants with an average age of 29 years ($SD \pm 6.00$). All participants held on average of 11 years ($SD \pm 6.00$) of driving experience.

The tactile belt was used to provide navigation aid in all driving sessions and the voice of the participants was captured during the experiments. We have conducted an interview at the end of each session with the participants.

4.2 Design and Procedure

Our pilot study contained one independent variable i.e. turn-by-turn directions and distances are presented to the drivers with vibro-tactile signals. We compared four different vibro-tactile encodings in the four sessions of driving for displaying the spatial information to the drivers. Each participant drove with the help of 4 different designs on an urban road. We measured the error rate of drivers of recognizing the correct direction for every vibro-tactile signal. On each crossing the wrong interpretation of the direction by the participant was considered as a direction error. Additionally we interviewed the participants about their preferences of vibro-tactile encodings after the experiments.

The participants wore the tactile belt around the waist. We trained all participants for each of the 4 different vibro-tactile encodings and instructed them to think aloud regarding directions while driving. The experimenter seated next to the driver was controlling the *tactile spatial display*. The participant was following the route according to the vibro-tactile instructions and announcing aloud the different directions. We changed the order of the four tactile encodings for each of the participants to avoid learning effects. Before the first session we trained the participant on the first vibro-tactile encoding in the sequence. After completion of first driving session we interviewed the participant regarding the design. We repeated the same sequence of steps for the other designs. Each of the participants drove 4 sessions on 4 different vibro-tactile encodings in a real urban environment. For each design the participants drove on the average 37 crossings ($SD \pm 0.82$). Each test session took around 20 minutes including the training, the driving and the interviewing.

4.3 Results

In this section we will present the quantitative results showing the errors made by the participants in interpreting the direction information and qualitative results representing the design preferences of the participants.

Errors in perception of the direction:

The participants were able to interpret all vibro-tactile signals of the *tactile spatial display*. They were able to correctly recognize all directions in the *one vibrator with distance design*. In the *two vibrators front design* the participants were often identifying front-right as a right direction The participants made errors of identifying left as front-left, front-left as left, and front-right as right direction in the *two vibrators side design*. In the *one vibrator design* the participants made mistakes of identifying left as front-left and front-right as right direction.

Qualitative results: We collected qualitative data from the interviews. The participant liked the tactile display on crowded road "Having vibration on torso is quite good in situations where lot of pedestrian and distraction otherwise and it worked well". All participants preferred *one vibrator with distances design* over all the designs for the *tactile spatial display*. In the following we will report the feedback of participants on each design.

	Left	Right	Front-left	Front-right
One Vibrator with distance design	0%	0%	0%	0%
Two vibrators front design	0%	0%	0%	20%
Two vibrators side design	5%	0%	25%	60%
One Vibrator design	5%	0%	0%	33%

Table 1: The percentage scores indicate errors made by the participants to identifying the directions in all designs

Direction perception: The participants of the pilot study were sure that they made no errors in perceiving directions using *one vibrator with distance design.* In all other designs participants think that they made 2 or less mistakes in identification of directions.

Need of distance presentation: The participants stated that it is very important to present distance. "It is very important to have distance presentation because you need to prepare for turn so it is really important to be informed in advance". The presentation of information in *one vibrator design* is dangerous for the driving safety. "At one point I had to stop hard which was certainly dangerous and at one time I even missed the crossing". "It is very important to receive information right before the turn and with fuzzy GPS the information presentation of *one vibrator design* will not work".

Need of an additional display: One participant did not need any additional display with the tactile display. The other participants required the visual display with the tactile display.

Activation of two vibrators: Simultaneous activation of two vibrators for *tactile spatial display* was not liked by the participants. "Simultaneous activation of two vibrators was quite confusing for me and hard to distinguish". It was difficult to differentiate the two adjacent directions. "It was difficult to feel front-left and front-right in *two vibrators side design*". "Two tactons have strange feedback".

One vibrator with distance design: The participants preferred the combination of one vibrator with distances. "It is nice, I like it – It is helpful to have additional distance presentation and not distraction like *two vibrators front design* and *two vibrators side design*". "It is better and easy to understand". "Easy to understand and perceive".

4.4 Discussion

The results provide us the proof-of-concept that the tactile belt is helpful to convey multiple directions and distances. With no errors, the participants verbally reported that they feel confident in using the *one vibrator with distance design*. So, our findings support the block design proposed by [7], combined with distance presentation. We chose the *one vibrator with distance design* for our further evaluations.

Distance presentation: The results showed that distance presentation increased the accuracy of information perception. The qualitative results showed that in the *one vibrator with distance design* the participants feel more confident and secure as compared to the *one vibrator design*.

Performance: It is difficult to decide between *one vibrator with distance design* and *two vibrators front design* on the basis of the quantitative results.

Although we conducted this study only with three participants but observations and comments of the participants helped us a lot to know the pros and cons of the designs. One of the limitations of the study was gender aspect. We conducted the study in the urban environment so we are not certain that the designs can be applied to other scenarios e.g. motorways.

5. EVALUATION

We conducted the evaluation to measure the cognitive workload, performance and distraction of drivers in a high load environment while performing a navigation task with a conventional car navigation system and a tactile display. The evaluation was done in a real urban environment. We assigned an additional task to the drivers along with task for following the car navigation system and the tactile display. The purpose of the additional task was to create a high workload environment for the drivers.

van Erp and van Veen [8] discovered that tactile navigation displays reduce the driver's workload compared to visual displays in a high workload environment. The previous findings raise the question whether tactile displays will help to reduce the cognitive workload, increase the performance and reduce distraction of the driver compared to conventional car navigation systems in high load situations. Thus, we aim to answer the following research questions in our evaluation:

Q1: How does the presentation of the multiple directions and distances with a tactile display affect the cognitive workload of the driver in a high demanding condition?

Q2: What is the level of performance of the participants on the secondary task while following the commands of a conventional car navigation system compared to a tactile display?

Q3: Does the presentation of the multiple directions and distances with the tactile display distract drivers from a secondary task?

5.1 Experiment Design

In our experiment we compared the presentation of turn-by-turn information with a conventional car navigation system and a *tactile spatial display*. The *one vibrator with distance design* was used to present information with the tactile display. We compared two experimental conditions: control group – conventional navigation system – and experimental group – *tactile spatial display*–. The participants had to perform the PASAT [4, 3] test in three conditions i.e. driving a car, driving and navigation task with the help of the conventional car navigation system, and *tactile spatial display*.

Our dependent measures are cognitive workload, distraction level and performance.

Cognitive workload: We measured the cognitive workload of the drivers by measuring their performance on the secondary task of PASAT while driving and performing the navigation task. X is the performance of the driver on PASAT in simple driving condition. The symbol Y is used to present the performance of the driver on the task of PASAT in navigation with the conventional car navigation system condition. The performance of the driver on PASAT in condition of the tactile display is presented by Z. The cognitive workload of the drivers can be calculated for the conventional car navigation system and the tactile display by the following algorithm:

if $(X-Y) == 0$ *or* $(X-Z) == 0$ **then**
  No change in cognitive workload
end if
if $(X-Y) < 0$ **then**
  Tactile display reduces cognitive workload
else
  if $(X-Y) > 0$ **then**
    Tactile display increases cognitive workload
  end if
end if
if $(X-Z) < 0$ **then**
  Car navigation system reduces cognitive workload
else
  if $(X-Z) > 0$ **then**
    Car navigation system increases cognitive workload
  end if
end if

The results of the drivers' cognitive workload while using the car navigation system and the tactile display can be interpreted with the help of following algorithm:

if $(X-Y) > (X-Z)$ **then**
  Car navigation system imposed more cognitive workload
end if
if $(X-Y) < (X-Z)$ **then**
  Tactile display imposed more cognitive workload
end if
if $(X-Y) == (X-Z)$ **then**
  Equal amount of cognitive workload
end if

A negative value means a reduction in cognitive workload. Zero indicates no change and a positive value an increase in the cognitive workload.

Performance: We measured the performance by counting the number of the wrong responses of the drivers in PASAT. Furthermore, we also compared the disorientation of the drivers using the *tactile spatial display* and the conventional car navigation systems. The disorientation occurs when the driver missed the intended turn.

Distraction: The distraction of the driver was measured by comparing the count of numbers that the participants were unable to answer on PASAT. We compared the tactile display with the conventional car navigation system with respect to level of distraction.

5.2 Participants and Apparatus

Overall, 10 participants of average age 32.8 year ($SD \pm 5.90$) took part in the evaluation. The sample contained 5 male and 5 female participants. The participants were driving license holders since an average of 12.9 years ($SD \pm 7.40$). The sample contained 1 beginner, 7 experienced and 2 expert users of car navigation systems. We conducted sessions in a dense urban traffic condition and tested 1 male and 1 female participants before the actual evaluations. The participants reported that it was safe to perform the secondary task while driving on the road in both conditions.

We used a Volkswagen Touran car in our evaluation. A built-in conventional navigation system – RNS 310, Navigation Radio System – was used for navigation purposes[5]. The conventional car navigation system contains a clear 5 inch color screen displaying a map of the route. A speech based interface guides the participants to the destination via speech interface. Our tactile belt was used as the *tactile spatial display*. The controller of the tactile belt was connected to the laptop of the experimenter. We used PASAT as an additional secondary task to perform during the experiment.

During the experiments oral feedback of the participants was recorded. At the end of all sessions, we asked some interview questions regarding the participants' impressions on the tactile display

[5]http://www.volkswagen.co.uk/new/touran/explore/experience/comfort/rns-310-navigation/radio-system

and engagement with the environment.

5.3 Procedure

The experimenter was seated next to the driver. On every turn the direction information combined with distance signal is presented to the participant. For longer streets the four categories of distances were presented, otherwise three or two categories. The participants were trained on the *one vibrator with distance design* and the secondary task PASAT before the experiments. For this second task the participants were required to count numbers and tell the sum aloud while driving without using any navigation system, using the conventional car navigation system and using the tactile display.

In previous studies [4] the evaluations have been done on 2 seconds (sec) and 3 sec trails of PASAT. The 2 sec and 3 sec trails of PASAT as secondary tasks were long enough to collect data on the road conditions. In each condition first we played a sequence of numbers with the pace of 3 sec and then 2 sec. Four different sequences of numbers were presented to the participants in the whole experiment. In PASAT the driver hears a male voice saying sequence of 50 numbers from 1-9. The driver adds the first number to the second number and tells the sum aloud. Then the participant is required add this sum to the next number and so on.

First the driver needed to count the sequence of number only in the driving condition. After completing the first task the drivers had to reach at another destination by following commands of the car navigation system and performed secondary task PASAT. Next we provided the training session to the participants with the tactile display while driving. In the last session the driver had to count the numbers of the provided sequences of PASAT during navigating with the tactile display. The whole experiment lasted about 1.5 hours included stops before the next session, data storage, and interview. On average each participant drove a distance of 14 km.

6. RESULTS

We analyzed the audio recordings of the participants' responses on PASAT. The right response, wrong response, and missed response are considered during data analysis. We calculated descriptive statistic for every dependent variable. The sophisticated statistical analysis could not be applied because of low number of the participants.

6.1 Quantitative results

Cognitive workload: Figure 5 shows the comparison of cognitive workload of the drivers using the conventional car navigation system and the tactile display. The results are calculated and interpreted according the algorithm given in Section 5.1. The participants 2 and 6 have a reduced cognitive workload on the conventional car navigation system while performing the secondary task PASAT-3 sec. Participant 1 reduced the cognitive workload on the tactile display while performing on PASAT-2 sec. Participants 8 and 9 have no change in cognitive workload on the tactile display while performing on PASAT-3 sec.

Participants 1, 8, and 9 reduced the cognitive workload on the tactile display as compared the conventional navigation system while performing on PASAT-3 sec. Participants 1, 4, 8, and 10 showed a reduced cognitive workload load on the tactile display as compared to the conventional car navigation system while performing PASAT-2 sec.

Gender differences: In Figure 6 showed a comparison of the errors made by male and female participants in both conditions of the tactile displays and the car navigation system in highly demanding environment. The male participants made more errors than the females participants on conventional car navigation system–PASAT-3 sec 64% , PASAT-2 sec 66% –. Similarly, the male participants made more number of errors than the females participants on the tactile display–PASAT-3 sec 69% , PASAT-2 sec 79% –.

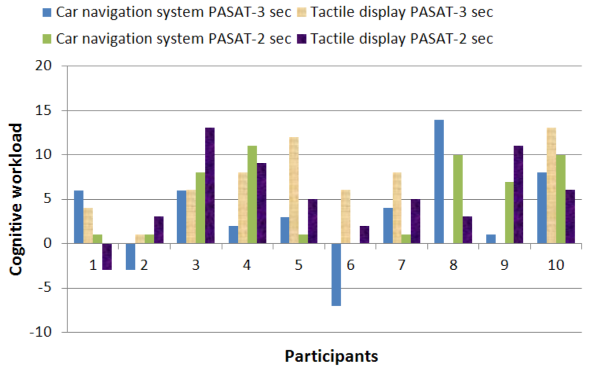

Figure 5: Measurement of cognitive workload of the participants

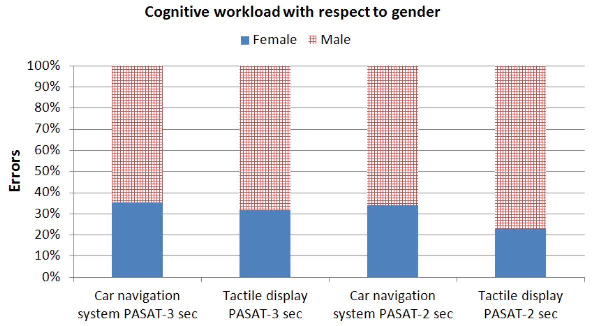

Figure 6: Male and female difference of cognitive workload

Performance: Figure 7 presents a comparison of the performance of the participants on the secondary task while driving with conditions of the tactile display and the conventional car navigation system. On PASAT-3 sec and PASAT-2 sec the participants made 36 errors using the tactile display and 38 using the conventional car navigation system. Participants 1 and 2 made an equal number of errors on PASAT-3 sec on the conditions of the tactile display and the car navigation system. Participants 3, 4, 5, 7 and 9 made less number of errors on PASAT- 3 sec with the tactile display as compared to the conventional car navigation system. Participants 5, 6, 7 and 8 made less number of errors on PASAT- 2 sec with the tactile display as compared to the conventional car navigation system

Figure 8 presents the number of errors made by the participants while following the navigational commands of the tactile display and the conventional car navigation system. The results show that the participants were disoriented 14 times using the conventional car navigation system. However, the participants were disoriented only 2 times while using the tactile display.

Distraction: Figure 9 presents a comparison of the level of distraction using the tactile display and the conventional car navigation system. Participants 1, 5, 7, 8 and 10 were less distracted on PASAT-3 sec with the tactile display as compared to the conventional car navigation system. Participants 1, 6, 7, and 10 were less distracted on PASAT-2 sec with the tactile display as compared to the conventional car navigation system. Participants 4 and 5 were equally distracted on PASAT-2 sec using the tactile display and the conventional car navigation system. Participants 5 and 3 did not

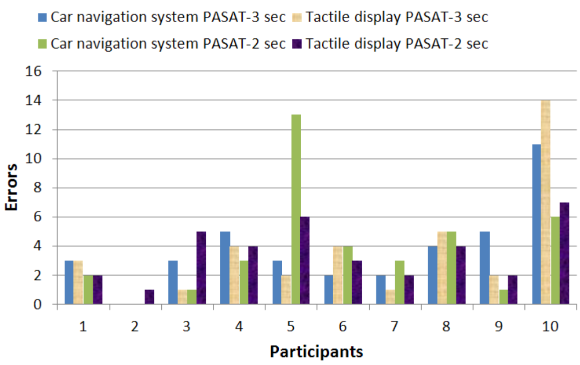

Figure 7: Comparison of performance of the participants on PASAT-3 sec and PASAT-2 sec on the conditions of car navigation system and the tactile display

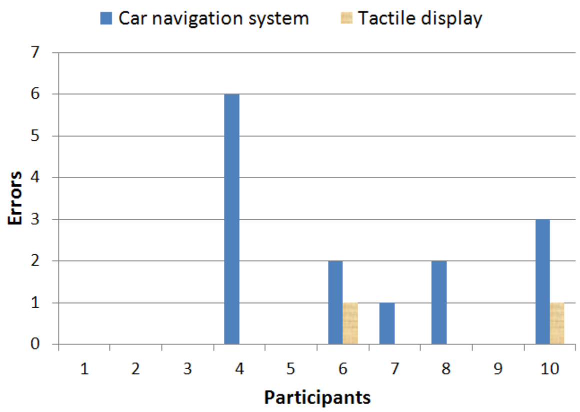

Figure 8: Comparison of drivers' orientation performance on conventional car navigation system and the tactile display

get distracted on PASAT-3 sec with the tactile display condition. Furthermore, the participants were unable to count the questions in the secondary task in a total of 113 times and 111 times by using the conventional car navigation system and the tactile display respectively.

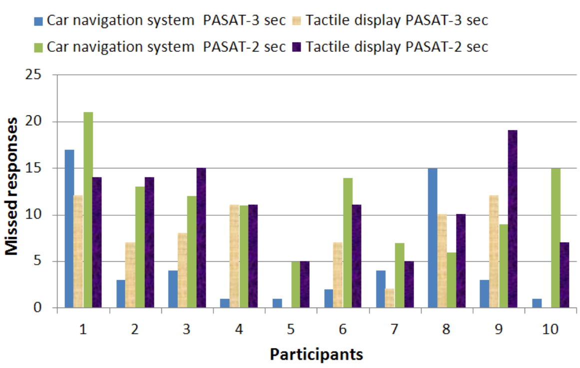

Figure 9: Comparison of distraction of the participants on PASAT-3 sec and PASAT-2 sec on the conditions of car navigation system and the tactile display

6.2 Qualitative results

The qualitative results report the responses of the participants on interview questions and observations. We asked questions regarding their performance in experiment, and engagement with the environment –streets names, signal crossings, bricked roads – while driving with the tactile display.

The interpretation of the tactons that present the direction was very easy for 6 participants. 4 participants reported that they faced problems in identifying the "front-right" and "front-left" directions. 6 participants did not report any problems in distinguishing the different distances. "The vibro-tactile distance encoding works well but it is demanding". "Sometimes I was unable to remember different counting of pulses, but it works fine when there were 2 pulses or 1 pulse." One participant had problems in differentiating between "near" and "far" and one participant was unable to differentiate between "very-far" and "far". Another participant was unable to remember the counting of vibro-tactile pulses while counting the numbers on PASAT.

The tactile belt did not cause any distraction according to the 8 participants. The tactile belt was a bit distracting according to 2 participants. 7 participants reported that they did not remember the names of the streets but one of them was able to remember the names of 2 streets. 9 participants remembered that they crossed a bricked road while driving with the tactile display. All the participants remembered that they passed by crossings with signals approximately 4-15 times.

7. DISCUSSION AND CONCLUSION

The results show that the *tactile spatial display* helps drivers to successfully navigate in an urban environment. The results did not show differences in the cognitive workload of the drivers on the tactile display and the conventional car navigation system condition. The participants were able to perform equally well on PASAT by using the tactile display and the conventional car navigation system. The orientation performance of the participants was better on the tactile display as compared to the conventional car navigation system in high load conditions, besides the fact that the majority of them were experienced users of the car navigation system. The participants were equally distracted on the secondary task in both the tactile display and the conventional car navigation system condition. In the following we will discuss our research questions according to our qualitative and quantitative findings.

Q1: How does the presentation of the multiple directions and distances with a tactile display affect the cognitive workload of the driver in a high demanding condition? Though, we cannot conclude from the results that a tactile display either increases or decreases the cognitive workload of the drivers compared to a conventional car navigation system. However, the tactile display helped the participants to navigate and engage with the environment in high demanding conditions. Our findings do not support the findings of van Erp and van Veen [8] that the tactile display decreases the workload of the drivers. This might have many reasons: (1) We compared the tactile display with a conventional car navigation system (visual and auditory) and the participants were experienced users of such a system (2) Our driving environment was more complex than in the car simulator and the drivers had to take care of multiple security related aspects. (3) We presented multiple directions with multiple distances with the tactile display.

Q2: What is the level of performance of the participants on the secondary task while following the commands of a conventional car navigation system compared to a tactile display? The results do not indicate a major difference in the performance of the participants on the secondary task of PASAT between both conditions of the tactile display and the car navigation system. The results indicate the orientation performance of the participants on the tactile display is better than the conventional car navigation system. Participant 2 made the least number of errors on PASAT, improved orientation performance, and a lower cognitive workload on both conditions. The participant was confident about the perception of the *tactile spatial display*. So, it shows that the reduction in cognitive workload causes a performance improvement. Similarly participant 10 made a maximum number of errors on PASAT, made errors on the orientation performance, and has increased cognitive workload in the both conditions. Furthermore, the participant was unsure regarding the perception of the "front-left" and "front-right" direction. In this case, increased cognitive workload degraded the performance of the participant. In this study, we might conclude that high cognitive workload cause decline in performance of task and it varies from person to person.

Q3: Does the presentation of the multiple directions and distances with the tactile display distract drivers from a secondary task? The results did not show a huge difference on the level distraction of the participants from the secondary task PASAT in both conditions of the tactile display and the conventional car navigation system. Participant 1 was distracted the most on PASAT among all participants but showing lower cognitive workload in the conditions. This means that the participant was less concentrating on the secondary task. Participant 5 was least distracted from secondary task of PASAT in the condition of the tactile display and the conventional car navigation system. Furthermore, the participant showed a maximum decrease in performance on PASAT-2 sec. Being a beginner user of a conventional car navigation system the participant showed less cognitive workload in the tactile display condition compared to the conventional car navigation system. The results showed that less distracted participants showed a higher chance to carry out the secondary task which might result in an increase or decrease of their performance on the task according to difficulty level. We might conclude that if the car navigation systems will grab less attention then the drivers will get a chance to perform other tasks in the car.

The results showed that counting a number of pulses in the tactile display were perceived as equally distracting as the conventional car navigation system (visual and auditory). In the training session the male participants performed better on PASAT than the female participants. The female participants performed better on PASAT than the male participants on conditions of the tactile display and the conventional car navigation system. This supports the findings [15] that the women have better ability to do multitasking in the high load conditions. Being beginner users of the tactile display most of the participants were confident on their perception of *tactile spatial display* which encourages the use of the tactile display in the car navigation systems. The tactile display helped the participant to engage with the environment.

Most of the participants were experienced users of conventional car navigation systems and beginner users of the tactile display. We conducted our study in an urban environment, so we cannot generalize the results for the other scenarios e.g. for motorways. The results can also not be generalized for the elderly drivers.

However, tactile displays might be helpful to decrease the reaction time in an emergency situation where the driver needs to observe the situation using visual and acoustic senses. So we conclude that the tactile display can effectively complement visual and auditory interface for successful task fulfillment in high load conditions.

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