Comparing Haptic and Audio Navigation Cues on the Road for Distracted Drivers with a Skin Stretch Steering Wheel

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***Abstract*— A steering wheel modified to produce lateral skin stretch provides perceptible cues in a vehicle being driven on the road. We conducted tests to determine whether drivers can correctly perceive and react to skin stretch navigation cues. Additionally, we compared skin stretch feedback to audio navigation cues during an auditory N-back distraction task simulating a phone call. Results show a statistically significant difference (p-value = 0.044) between haptic (98.5%) and audio feedback (96.6%) in navigation accuracy and in N-back response accuracy (haptic = 89.9%, audio = 87.2%, p-value = 0.047).**

I. INTRODUCTION

Despite many advances in safety technology, there is evidence that crashes may be growing more prevalent, due to increasing driver distraction from cell phones, navigation systems, etc. [1], [2]. Although most countries have imposed "hands-free" rules for cell phones, studies show that even hands-free calls distract the driver [3].

Haptic feedback is a relatively underused sensory channel during driving, and has the potential to capture the driver's attention in environments having distracting audio and visual stimuli. Wickens et al. demonstrate that humans are able to process information through multiple sensory channels simultaneously, and that it can be beneficial to spread stimuli across different modalities to prevent any one channel from becoming saturated [4], [5].

Lateral skin stretch is a particularly rich form of haptic feedback, capable of providing magnitude and direction information [6], making it well suited to convey navigational stimuli in a vehicle. In this paper, we employed a steering wheel that provides a lateral skin stretch haptic display and asked drivers to navigate an unknown course in a suburban neighborhood. To continuously assess distraction and cognitive load, we asked them to provide responses to an auditory "N-back" question and answer task – comparable to conducting a coherent phone conversation [7].

We hypothesized that subjects would generally do well in perceiving and reacting to haptic navigational stimuli based on previous work [8], and that performance would be better with haptic cues than with audio cues due the sharing of the same sensory channel between the audio cues and N-back task, as well as the ability of the skin stretch cues to convey direction in a way that humans understand reflexively.

We conducted tests with 10 users on a pseudo-randomly chosen course with a balanced order of audio and haptic conditions, and found evidence supporting our hypotheses. This work's primary contribution is the testing of lateral skin stretch cues for driver navigation in a realistic on-the-road environment.

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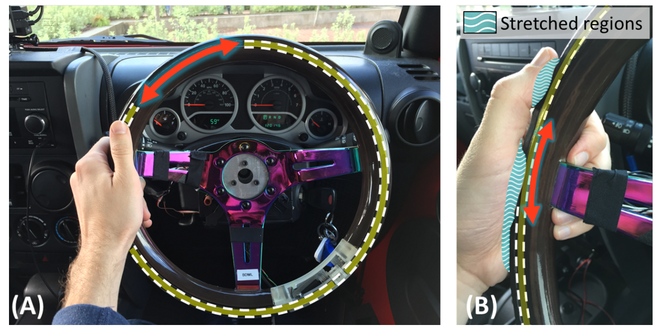

Fig. 1. (A) Skin stretch steering wheel display: ring at front of the rim shown in yellow highlighted region with dotted line can rotate ± 0.5 degrees, producing ± 2.5 mm of skin stretch, and can be gripped anywhere. Integrated motor is visible at the 5 o'clock position. (B) Close-up view of the skin stretch. The palm and thumb pad are the most likely areas to be stimulated.

We conclude with a discussion of particular effects observed and avenues for future work.

II. PREVIOUS WORK

Significant work has been done examining haptic feedback, usually vibrotactile, as a means of assisting navigation [9]–[14]. For example, Hwang and Ryu explored design parameters for communicating navigation information with a vibrotactile steering wheel using a bench top setup [15], and Kim et al. compared younger and elder drivers' attentiveness to driving while receiving route guidance through a vibrotactile steering wheel in a simulator [16].

Several studies have also specifically addressed the issue of driver distraction with haptic feedback. Medeiros et al. found in a simulator study that subjects distracted by a phone call performed better with skin stretch haptic feedback than audio in a lane-change task [17]. Mohebbi et al. showed in a simulator study that audio cue reaction time was affected more significantly than haptic cue reaction time when the driver was having a phone conversation [18]. Szczerba et al. found that a vibrotactile display embedded in glasses improved speed-keeping and attention secondary task performance in a driving simulator compared to a visual-auditory navigation system [19]. Van Erp and Van Veen tested a vibrotactile seat against a visual display in a driving simulator navigation study and found that haptic combined with visual feedback resulted in better perfomance and reduced workload [20]. Stanley showed that vibrotactile feedback at the seat had faster reaction times than audio feedback in a lane departure warning simulator study where subjects were given a distracting memorization task [21].

As seen above, most studies have taken place in simulators, though a small amount have been run on-road. For example, Fitch et al. found improved reaction times to a surprise barrier when using seat vibration in a closed course road study. [22].

While simulator studies have the advantage of providing highly controlled driving scenarios, they do not realistically reproduce the mental tasks and haptic environment of a car on the road. We previously studied humans' ability to perceive skin stretch feedback while in a moving vehicle, but as passengers [8]; in this paper, subjects were driving while interacting with the device.

III. HAPTIC DEVICE

The haptic device used in this research is a steering wheel with a lateral skin stretch display embedded in the front surface of the rim, seen in Fig. 1 (A), and is the same as that used in our previous work [8]. The surface of the display, a large, thin ring located on the rim face, allows the driver to easily make contact with the hands regardless of where he or she grips the wheel, or whether using one hand or both. A small DC motor[1] and lead screw mechanism inside the rim rotate the display surface clockwise or counterclockwise (Fig. 2). This rotational motion laterally stretches the contacting skin of the driver's hands, usually the palms and thumb pads (Fig. 1 (B)).

The display is able to provide 11.4 N of force from the motor, a maximum skin stretch displacement of 2.5 mm, and a bandwidth of approximately 15 Hz when not gripped and 7 Hz when gripped. The force capability is adequate to produce the estimated force (2.34 N) required for skin stretch of the driver's palms [8]. A bandwidth of 15 Hz was desired, as this is the frequency at which it becomes difficult to distinguish directional cues from vibrations due to the low spatial resolution of Pacinian corpuscles [23]. While not reaching the upper frequency limits of human lateral skin stretch sensitivity, the device has enough bandwidth to render the low frequency directional cues desired for this experiment [8]. Sensing is accomplished with the DC motor's rotary encoder[2], supplemented by a linear Hall Effect sensor measuring the absolute bearing position directly. This check of absolute position is necessary due to compliance in the lead screw mechanism. A positioning error of 0.06 mm or less was achieved for skin stretch cues [8].

[1]Faulhaber 1224 brushed DC micromotor

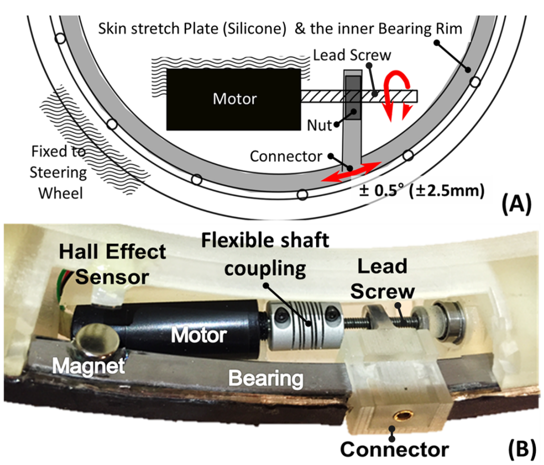

Fig. 2. (A) A lead screw and nut are mounted to a 3D-printed connector, which is attached to the inner ring of the bearing to rotate it ±0.5 degrees. (B) Close up view of the actuation and sensing elements, including motor and flexible shaft coupling.

IV. EXPERIMENT SETUP

We developed an on-road experiment to test the effectiveness of the skin stretch steering wheel, where we asked subjects driving a vehicle to follow a route using haptic or audio navigation cues, while at the same time responding to an auditory N-back distraction task simulating a phone conversation. Components of the setup are described below.

A. Vehicle

The original steering wheel of a right-hand-drive 2010 Jeep Wrangler vehicle was replaced with our skin stretching haptic steering wheel. This vehicle naturally has large amounts of ambient vibration when driving that can potentially mask other haptic stimuli, making it a rigorous test of the effectiveness of the skin stretch cues. While the subjects in this study were not experienced in driving on the right side, they were given time to adapt by driving to the starting location of the experiment (3.2 km). The setup is shown in Fig. 3. The subject sat on the right side and drove the vehicle normally while receiving skin stretch feedback. The experimenter sat on the left and triggered haptic or audio cues with a laptop and microcontroller.[3]

To collect data, three video cameras were set up in the vehicle: one facing the road, one facing the subject, and one behind the subject facing the steering wheel.

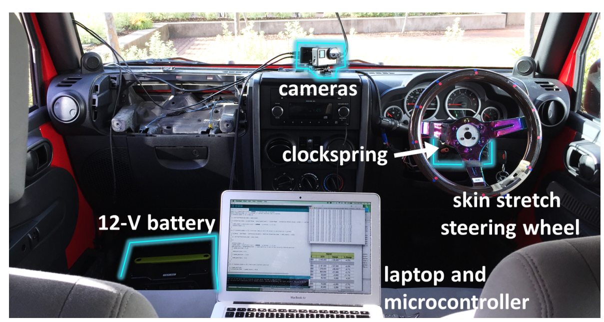

Fig. 3. The experimental setup in the vehicle consisted of the haptic steering wheel attached to the steering column, a clockspring to route the wiring, a laptop and microcontroller for the experimenter to control the haptic and audio cues and auditory N-back task, a camera system for data collection, and a 12 V battery to power the haptic motor.

B. Driving Route

Desirable qualities for the experiment driving route included having moderate levels of traffic for appropriate task difficulty, being located nearby the subject pool at Stanford University for practicality, and having a large number of densely-spaced intersections. In order to satisfy these requirements a nearby area (3.2 km from subject starting

[2]HEM3-256W
[3]Teensy 3.2 https://www.pjrc.com/teensy

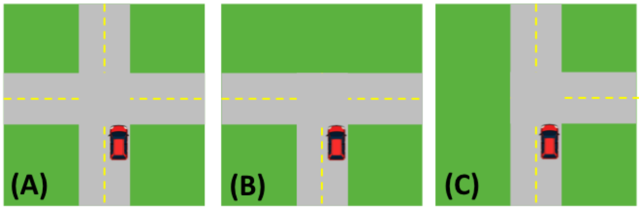

Fig. 4. Three turn categories: A) Crossroads B) T junction approached from stem C) T junction approached from arm

location) was chosen consisting of residential neighborhoods surrounding a moderately busy four-lane road with a top speed limit of 35 miles per hour. Most importantly, the surrounding roads make up a grid approximately 12 blocks long by 2 blocks wide, providing many intersections that are close together.

To compare haptic and audio feedback within subjects, two routes were used to prevent memorization between trials. These could be thought of as planned routes, as the actual routes would vary due to navigation errors of the subjects, Still, we sought to balance the number of different kinds of turns between them as much as possible, often using the same turns but out of order or approached from a different direction. The three main turn categories encountered were crossroads, T-junctions approached from the stem, and T-junctions approached from one of the arms, as depicted in Fig. 4. Each turn scenario has different options for subject error: a crossroads allows the driver to miss a cue or misinterpret the direction; a T-junction approached from the stem forces a turn, so the subject can misinterpret direction but cannot miss a cue; a T-junction approached from an arm allows a cue to be missed but not misinterpreted. Crossroads then are the most difficult to correctly react to, so we chose to include as many as possible.

The chosen planned routes had nearly identical lengths, identical start and end points, similar sets of turns, and qualitatively felt similar in difficulty but different enough to be unpredictable. Route 1 was approximately 3.6 km and had 22 total turns (10 left and 12 right), of which 14 were crossroads, 4 were T junctions approached from the stem, and 4 were T junctions approached from the arm. Route 2 was approximately 3.5 km and had 24 total turns (11 left and 13 right), of which 16 were crossroads, 3 were T junctions approached from the stem, and 5 were T junctions approached from the arm.

C. Daze Application

To guide drivers through the route and initiate cues consistently before turns, the experimenter used a mobile application called Daze designed to mimic a driving navigation program [24]. The application features a map, the actual vehicle location, and the ability to drop pins on the map that trigger a notification when entered. The experimenter used this feature to initiate navigation cues at a consistent radius from intersections of 76.2 m (250 ft), as shown in Fig. 5. The application updates at a rate of 1 Hz and has an approximate vehicle position error of 2.5 m or less.

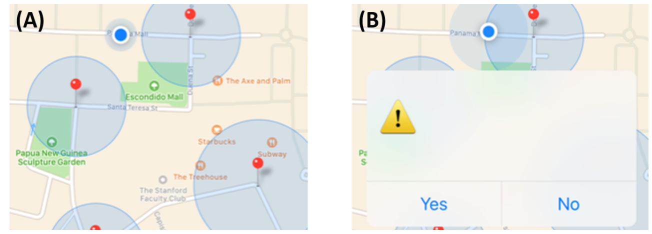

Fig. 5. Screen captures from the Daze application showing how pins can be dropped with a set radius that provide notifications when entered. (A) Before entering radius. (B) Just after entering radius, with corresponding alert shown.

D. Haptic Navigation Cues

Haptic navigation cues rendered with the steering wheel consisted of a double pulse of a 12 mm/s ramp-up, followed by a short pause, and a ramp-down at 10% speed, as shown in Fig. 6. The double pulse was chosen as suggested in [6]; having a priming pulse in skin stretch was especially important in this experiment due to constantly changing hand positions.

Subjects were instructed to turn in the direction of the fast ramp-up portions, where clockwise rotation signified a right turn and counterclockwise signified a left turn. The speed and displacement were chosen based on the results of [8] to be large enough to be perceived easily over ambient vehicle vibrations.

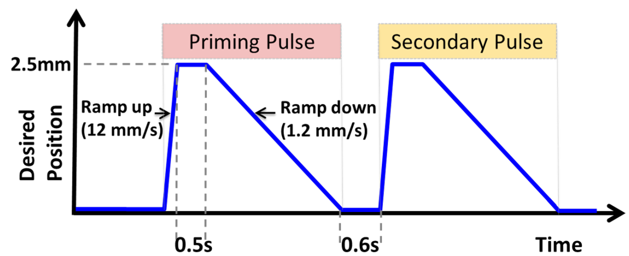

Fig. 6. Each haptic stimulus consisted of a double pulse of a 12 mm/s ramp-up to 2.5 mm, a 0.5 second pause, and a 1.2 mm/s ramp-down to zero. The time between pulses was 0.6 seconds.

E. Audio Navigation Cues and N-Back Auditory Task

Audio navigation cues, chosen as a control stimulus type to compare to the haptic cues, consisted of audio recordings of the words “left” and “right” created with a voice synthesizer. These cues were triggered by the experimenter using the Daze application. The volume level was clearly understandable but not overpowering, similar to a normal speaking voice or standard GPS navigation system volume level.

Additionally, an N-back auditory task was chosen as a secondary task that subjects must perform while navigating to increase cognitive load and provide additional auditory stimuli, similar to talking on a cell phone [7]. The N-back task stimulus consisted of a random stream of numbers between 1 and 10 recorded from a human voice and played at 3 second intervals through the vehicle speakers for the duration of each trial (haptic or audio feedback). This was done at the same volume as the audio navigation cues. The subject was asked after each number was played to speak aloud the number that was heard immediately before it, meaning that

$N = 1$ in this case. This was the maximum number that felt safe when driving in this distracting environment during pilot testing.

F. Participants

The subject population consisted of 10 students recruited at Stanford University, with 6 males and 4 females. The average age was 24.7 (ranging from 23 to 26), and the average amount of driving experience was 6.3 years (ranging from 3 to 10 years). All subjects' driving experience was with left-hand drive vehicles. There were originally 11 subjects, but one subject's data was not used because he had not received training with the haptic feedback, which has a significant learning effect. All tests were conducted under IRB Protocol 26526 to protect the rights and welfare of participants.

V. EXPERIMENT PROCEDURE

The experimental procedure was as follows: first, the subjects practiced the N-back task and experienced the haptic feedback until comfortable with both in the stationary vehicle. Then, they practiced with the haptic feedback alone, followed by the N-back task alone, on the road while driving to the route starting point.

Training was important due to the different feeling of the skin stretch feedback when actually driving in comparison to holding the steering wheel in a stationary environment. This arises from constant changes in grasping positions and forces while operating the steering wheel and navigating through turns and curves of the road. Subjects were allowed to grip the wheel in a variety of styles, with one hand or both, but were asked to make some contact with the front surface of the wheel during the haptic trials. They were also instructed to grip tightly enough to feel the skin stretch but not so much that they stalled the DC motor.

For both practice tasks, subjects were allowed to ask questions at any time to the experimenter. The audio navigation cues were self-explanatory and did not require training.

After arriving at the route starting point, subjects began the first of two trials, either the haptic navigation or audio navigation segment. After driving several minutes, the N-back task would begin, and the subject needed to be ready to respond to the navigation cues. The instructions were to turn in the direction perceived at the next available intersection. If a turn was missed or incorrect, the experimenter would guide them back to where they left the course through additional turns, if feasible. If not, substitutions were made, modifying the route. Subjects who made mistakes usually had a greater number of turns due to the addition of turns required for correction. Errors often resulted in turns being subtracted from the route as well, as the original turn and several following turns were commonly replaced by similar turns. These additional turns were added to the average, increasing the randomness of the routes, and were viewed as a necessary part of running experiments on the road. Subjects were not informed whether the turns made were correct or not during the experiment.

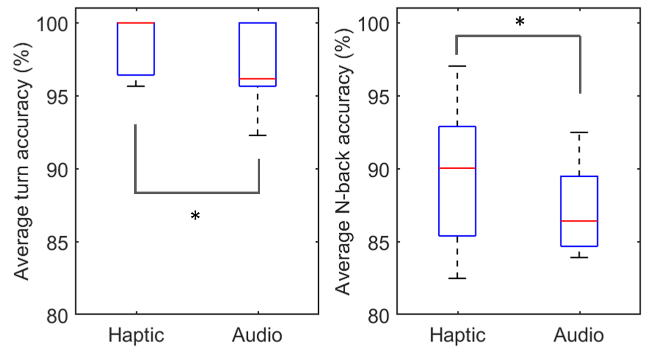

Fig. 7. (A) Average turn accuracy for haptic and audio cases. (B) Average N-back accuracy for haptic and audio cases. Boxes represent the 25^{th} to 75^{th} percentile of the data, the line is the median, and the whiskers show the entire range. The asterisk indicates statistical significance with a 95% confidence level.

When finished with the first trial, subjects drove back to the starting location and began the second trial after a short break. The task in the second trial of the experiment was the same as the first part, except that the type of feedback was switched. The condition was alternated so that half of the subjects performed the haptic part first while the other half performed audio first. Additionally, the planned route was switched between trials and order was alternated between subjects, but as mentioned, these contained unpredictable variations.

Experiments took approximately 1.25 hours to conduct, including 20 minutes each for the practice session, the haptic cue session, and the audio cue session, as well as some transition time. Experiments took place between 11:00AM and 5:30PM to ensure similar levels of moderate traffic.

After completing both trials, the subjects filled out a short questionnaire asking them to assess how difficult the navigation and N-back tasks were and which feedback type they preferred, as well as to report any errors they believed they made and what they thought caused them.

VI. RESULTS

Results show that subjects generally navigated with high accuracy, as seen in Fig. 7 (A). In total, 4 turns were performed incorrectly in the haptic case out of 255 total for all subjects, and 9 were performed incorrectly out of 258 for audio. The average percentage of turns completed correctly for the haptic case was 98.5% (SD=1.9%) while for the audio case it was 96.6% (SD=2.7%). Bartlett's test was used to verify that there was homogeneity of variances across samples, and the D'Agostino-Pearson test was used to confirm that the data was normally distributed. A two-tailed paired t-test confirmed that this difference in accuracy percentage between haptic and audio is statistically significant (95% confidence level, p-value = 0.044).

The relationship between turn accuracy and order (i.e., the difference between the first and second trial) was also examined with a two-tailed paired t-test to see if there was any effect of learning or fatigue, but none was found (95% confidence level, p-value = 0.324). While there were two routes in the experiment for increased variety, route was not considered a meaningful variable to test the effect of due to the unpredictable variation caused by navigation error. Changes in route between subjects were quite large, in some cases as many as 10 turns added (mean added turns = 3.75, SD = 3.19) and 4 turns subtracted (mean subtracted turns = 1.3, SD = 1.22) in planned routes that are only 22 or 24 turns long to begin with. Since actual route varied randomly between subjects, along with other variables like traffic conditions, pedestrian levels, etc., and we were not explicitly interested in the routes themselves, we simply accepted the randomness and balanced the planned route order across subjects and trials to minimize any effects.

In addition to turn accuracy, subjects' performance on the N-back task was analyzed. The percentages of correct N-back responses for the haptic and audio cases are shown in Fig. 7 (B). The average percentage of correct N-back responses in the haptic case was 89.9% (SD = 5%), and the average percentage of correct responses in the audio case was 87.2% (SD = 3.1%). This difference was confirmed to be statistically significant with a two-tailed paired t-test (95% confidence level, p-value = 0.047). The relationship between N-back accuracy and order was tested, and there was no statistically significant difference found (95% confidence level, p-value = 0.742).

In the post-experiment survey, eight of the subjects stated that they preferred haptic to audio, one preferred audio, and one had no preference. On a scale from 1-10 with 10 being easiest, subjects assigned an average score of 8.6 for ease of navigating with haptic feedback, 8.5 for ease of navigating with audio feedback, 6.2 for ease of responding to the N-back task during the haptic condition, and 4.8 for ease of responding to the N-back task during the audio condition.

VII. DISCUSSION

It was discovered that both navigation accuracy and completion of the N-back cognitive loading task were significantly related to the type of navigation cues received, and that haptic feedback was better in both cases.

Additional insight can be gained by examining the missed turns on an individual basis, using video footage taken.

A. Missed Turns with Haptic Feedback

Of the four missed haptic turns, two were perceived correctly by the subject but they reacted too slowly and missed the opportunity to turn. In one of these two, the missed turn was immediately after another turn onto a busy road, and required a lane change. The subject seemed to miss the initial haptic pulse because he was still turning the wheel back to the zero position and was not making good contact with the front of the rim. He then seemed distracted by the N-back task and reacted to the second pulse too slowly. This subject answered in the survey that he prioritized N-back over navigation. The other two missed turns were perceived but the turns were made in the wrong direction. In one of these, the subject initially perceived correctly and turned on the correct (left) turn signal. However, the turn signal happened to deactivate. He then turned on the right signal when reaching the turn and incorrectly turned right. In the survey he responded that he became confused because he felt the slow return stroke of the haptic pulse and interpreted it as a direction. That particular turn is also slightly confusing due to the curvature of the road, and this seemed to add to his confusion in the video. The other subject who turned in the wrong direction was seen to have his hands off the wheel during the initial pulse ramp-up stroke, and it is likely that he also misinterpreted the slow return stroke of the pulse as the commanded direction. He was apparently unaware of the mistake based on his survey responses.

B. Missed Turns with Audio Feedback

Of the nine audio mistakes, four were perceived correctly, but subjects were visibly distracted or reacted too slowly and passed the turns. In two cases, subjects did not perceive the stimulus or were so distracted that they had no reaction, and passed the turn. In one case, a subject perceived the stimulus, but forgot the direction by the time she reached the turn so went straight. In one case, a subject perceived the stimulus but immediately forgot the direction and made a wrong guess at the intersection. Finally, in one case, a subject confidently made a turn without receiving a stimulus.

C. Feedback Type Comparison

These missed turns qualitatively suggest a few things about the strengths and weaknesses of the two types of feedback. One of the major weaknesses of haptic feedback was that subjects confused the ramp-up and ramp-down portions of the pulse. The much slower speed of the ramp-down was intended to prevent this, but seemed to still cause confusion. Receiving haptic cues while in the process of turning the steering wheel also seemed to be difficult, which may be a result of the subjects making more contact with the outside of the rim than the front to exert greater torque, as well as weakness of the haptic motor. There was only one completely missed stimulus with a subject particularly focused on the N-back (according to his survey response), which again may be a sign that the haptic stimulus is too weak. However, haptic feedback had less missed turns overall, and seemed more easily noticed and reacted to.

The survey responses suggested a slight preference and greater confidence in haptic feedback over audio feedback. The reasons given included that it was generally intuitive to turn the wheel in the direction felt, as well as difficult to split auditory resources between the N-back and audio navigation tasks. Some noted that the haptic feedback was more difficult initially but grew easier as they became used to it. One subject preferred audio because he devoted significant cognitive resources to holding the wheel gently so as not to stall the haptic motor.

When perceived, direction of audio cues was not misinterpreted, but turns seemed more likely to be missed due to distraction, confusion, or forgetfulness. One subject mentioned that she had to rely on pressing the turn signal immediately when hearing the cue to turn correctly, because she simply could not remember the directions in the audio case, while she could in the haptic case. This suggests that the cognitive load of performing two verbal auditory tasks is high. The spontaneous turn without stimulus made by one subject also may be due to this saturation of the sense of hearing and of cognitive processes related to language.

In the case of N-back accuracy, haptic feedback also performed better than audio, suggesting that the haptic cues presented a smaller cognitive load than the audio cues when driving while aurally or verbally distracted. While the goal of this research is not to show that haptic feedback allows one to have a better phone call while driving, this result is still promising because it suggests that the cognitive load on drivers, especially aurally or verbally distracted ones, can be reduced with this novel interface.

VIII. CONCLUSIONS AND FUTURE WORK

In an on-the-road study, skin stretch haptic feedback has been found to be better than audio feedback in communicating navigation information to drivers experiencing auditory distraction, as well as in reducing cognitive load arising from auditory or verbal stimuli. While the differences in task accuracy may seem small, improvements of a few percent in automotive safety from reduced cognitive load will result in large benefits.

After finishing this study, a number of improvements for the device became evident, such as strengthening the haptic cues by using a more powerful motor, and moving the display surface to a location that provides better contact with the skin, potentially the outside of the wheel. The skin stretch stimuli could be improved by enduring longer than two pulses, so that drivers are able to check the direction more easily. To prevent drivers from missing cues, a simple capacitive touch sensor could be integrated into the skin stretch display, allowing cues only to be transmitted when the driver's hands are making contact. A design that does not utilize bidirectional cues would also help avoid confusion.

In terms of the study itself, it would be helpful to provide longer, more rigorous training to ensure subjects are used to the skin stretch cues. It would also be beneficial to expand the study by running a greater number of subjects, as well as increase the randomization of the routes. This could be done in a controlled way by mocking up a small, dense grid of roads in an empty parking lot.

Future experiments of particular interest include testing the usefulness of skin stretch for helping drivers with hearing impairments to navigate, testing navigation cues with middle-aged or older participants to determine how the perception is affected by age, and providing preview information about the intentions of autonomous and semi-autonomous vehicles.

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