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Haptic Skin Stretch on a Steering Wheel for Displaying Preview Information in Autonomous Cars

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***Abstract*— Lateral skin stretch is a promising technology for haptic display of information between an autonomous or semi-autonomous car and a driver. We present the design of a steering wheel with an embedded lateral skin stretch display and report on the results of tests (N=10) conducted in a driving vehicle in suburban traffic. Results are generally consistent with previous results utilizing skin stretch in stationary applications, but a slightly higher, and particularly a faster rate of stretch application is preferred for accurate detection of direction and approximate magnitude.**

I. INTRODUCTION

As modern cars incrementally gain autonomy and assume roles for which humans are traditionally responsible, it is increasingly important to keep the driver informed and in the loop. When the human does not know what actions the car is taking or why, they are likely to have increased anxiety and perform poorly if required to take control of driving again [1], [2]. A recent concept in human-vehicle interaction is that autonomous or semi-autonomous cars should give their drivers a preview of impending actions. For example, a semi-autonomous vehicle could warn the driver that the car intends to change lanes, make a turn, or exit a freeway, keeping the driver informed and at ease with the car's actions. A simulator study [2] demonstrated that verbalized messages previewing a semi-autonomous car's actions have the potential to increase driving performance and decrease negative feelings. Although audio and visual cues are standard ways of giving drivers information, here we explore haptic cues for their potential advantage of gaining the driver's attention more quickly and reflexively [3] without saturating the already heavily used visual and auditory channels [4].

An emerging mode of haptic feedback in automotive research is handwheel torque. For example, [5] used handwheel torque to provide lane keeping information, while [6] provided collision avoidance warnings. Beruscha et al. [7] provide a review of other instances where handwheel torque was used to relay information. Studies have demonstrated the efficacy of handwheel torque to communicate information, but it has the unfortunate effect of slightly steering the car and removing some of the driver's autonomy because the feedback is coupled with the steering system.

Another widely used modality in haptics, including automotive applications, is vibrotactile feedback. Among others, [8] and [9] displayed navigation information in a driving simulator using vibrotactile glasses, [10] gave forward collision

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Fig. 1. Skin stretch steering wheel display: ring at front of the rim shown highlighted in yellow 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

warnings through vibration of the steering wheel and seat belt, and [11] and [12] developed multi-actuator vibrotactile steering wheels that can transmit navigation instructions. However, while compact and easy to implement, vibration feedback is best suited for binary information as it can be difficult to distinguish among multiple sources or levels of vibration [13]. Driving tasks often relate to analog factors like direction, position, and speed, which are difficult to communicate with vibration alone.

One promising type of haptic feedback that has been effective in navigation tasks is lateral skin stretch. In lateral skin stretch feedback, a surface applies a shear force to the skin that excites a range of mechanoreceptors, including the slowly-adapting type II [14], [15]. It was shown in [16] that humans can distinguish between four directions of skin stretch of the finger pad with displacements as small as 0.2 mm and speeds as slow as 1 mm/s with greater than 95% accuracy. Skin stretch has been shown to be useful in navigation tasks [17], and it was demonstrated that humans are able to correctly interpret skin stretch of the thumb pads as GPS navigation cues while using a driving simulator [4]. If properly utilized in a car, skin stretch could prove to be more informative than vibrotactile feedback while requiring fewer actuators, as well as more pleasant to use than handwheel torque feedback because it does not steer the car for the driver. Potential applications for steering wheel skin stretch include navigation cues, collision avoidance warnings, blind spot monitoring, lane keeping, low traction warnings, driver training cues, and previews of autonomous car actions.

Although skin stretch shows promise as a means of facilitating communication from car to driver, it remains untested in actual driving environments where many other sources of haptic feedback and vibrations exist that could potentially mask it. There also has not yet been a display that is integrated entirely within a conventional steering wheel and accommodates a wide range of hand positions.

The first contribution of this paper is a compact skin stretch display that is embedded in a standard steering wheel and provides feedback regardless of hand positioning (Fig. 1). The display works as long as contact is made with the front of the rim; the positioning of the hands around the rim and decision to grip with one hand or two do not matter. Here, the glabrous skin of the palms is the most likely point of contact (Fig. 2). While generally less sensitive than the fingertips, it has a similar density of slowly-adapting type II mechanoreceptors [18], which have been shown to be most closely related to sensing skin stretch. Our second contribution is the demonstration in realistic on-road tests that humans can perceive the feedback and interpret direction and magnitude, even when competing against other sources of vibration as well as the distractions inherent in driving. However, stimuli must be somewhat stronger and faster than those shown to work in a laboratory environment.

II. HAPTIC DEVICE DESIGN

In a previous skin stretch steering wheel simulator study [4], skin stretch was shown to be effective in providing navigation instructions, but the driver was required to use a specific grip position with the thumbs contacting the tactors. The tactors also protruded from the wheel, modifying the form factor. To expand upon this work, our goals were to *i*) make the actuation fit inside a steering wheel rim and not significantly affect the form factor or inertia, and *ii*) deliver the skin stretch feedback for a wide variety of common grip styles that drivers use.

1) Lateral Skin Stretch Surface: The haptic device consists of an NRG 310 mm wood custom steering wheel with a large, thin-section bearing[1] embedded into the front of the rim. A groove was cut into the rim using a CNC mill, and a small section of the rim was removed and replaced by a 3D-printed box to house the actuator (Fig. 3).

[1] VXB VA110CP0 11x11.5x0.25”

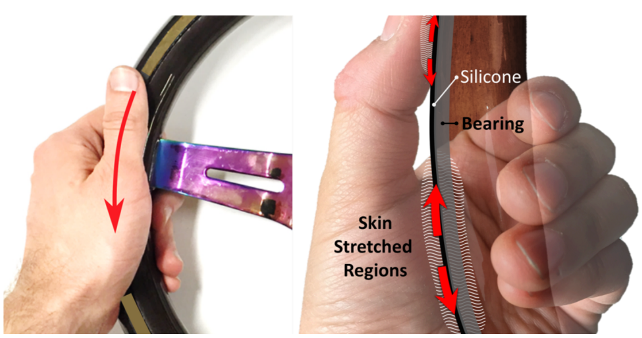

Fig. 2. Close-up view of the skin stretch produced by the steering wheel.

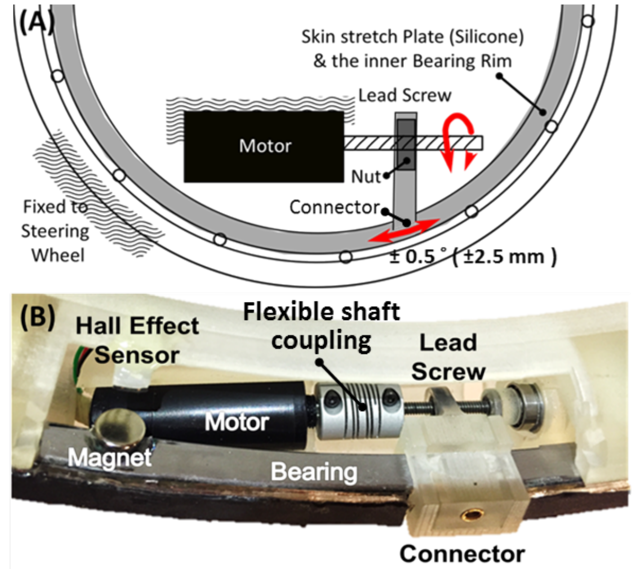

Fig. 3. (A) A screw and nut are mounted to a 3D-printed connector which is attached to the inner ring of the bearing to rotate it ± 0.5 degrees. (B) Close up view of the actuation and sensing elements, including a motor and flexible shaft coupling.

The inner ring of the bearing can rotate with respect to the wheel, and is powered by a lead screw actuator. The contact surface at the front of the ring is coated with 20 durometer silicone,[2] chosen due to its high friction with the skin. We selected this material after a brief qualitative survey of five subjects, where each was asked to rank the materials (3M Greptile, 20 durometer Silicone, and Dycem Nonslip Reel) in terms of comfort and perceived amount of stretch.

2) Actuation: The inner surface of the bearing is rotated up to 0.5 degrees clockwise or counterclockwise by a small lead screw actuator, corresponding to $\pm$ 2.5 mm of circumferential motion of the ring, as shown in Fig. 3.A. This motion creates lateral skin stretch in either direction at the palms of the user’s hands. The lead screw actuator consists of a Faulhaber 1224 brushed DC micromotor fixed to the wheel and connected to a 2-56 screw with a flexible shaft coupling. A small bearing fixed in the motor box supports the end of the screw opposite the motor, and a nylon nut translates along the screw, propelling the bearing through a connector. The slight misalignment resulting from converting linear to rotational motion is accommodated by compliance in the system.

The required actuation torque assumes a normal grip pressure of 4 kPA [19], which, based on the approximate area of the palms in contact and the friction coefficent between silicone and the human palm [20], leads to a required lateral force of 2.34 N. The Faulhaber 1224 motor can generate 11.5 N at stall while fitting inside the rim. The motor is controlled by a microcontroller (Teensy 3.2) and driver shield (Pololu VNH5019).

[2] HT6220 20 Durometer silicone 0.02”, Marian

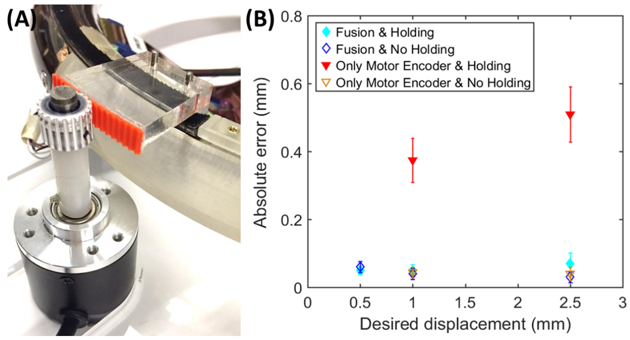

Fig. 4. (A) Set-up for position error test and bandwidth test. An external encoder was attached to the bearing to measure its absolute position. (B) Position control accuracy (average of absolute error and 95% interval)

3) Sensing: The primary sensor for the skin stretch feedback system is the motor encoder.[3]. A Hall effect sensor was added to check the feedback position, as described in the following section. A second encoder[4] reads the angle of the steering wheel when it is mounted in a car.

III. HAPTIC DEVICE CHARACTERIZATION

1) Position Accuracy: The accuracy of our position control was checked by an external optical encoder. The average position error was 0.042 mm ($\pm$0.018 mm) when no grip force was applied. However, when holding the wheel with a firm grip the error increased to 0.44mm ($\pm$0.07 mm), due to compliance in the coupling, and play in the motor shaft and the end-bearing for the lead screw. To compensate for this compliance, we have added a linear Hall effect sensor for direct position measurement of the inner ring of the bearing. With corrections made for the nonlinearity of the Hall effect sensor, the average positioning error for displacements in benchtop tests with 5 subjects was reduced from 0.44 mm to 0.06 mm ($\pm$0.02 mm) (Fig. 4).

[3]HEM3-256W
[4]Signswise 360pr Incremental Rotary Encoder

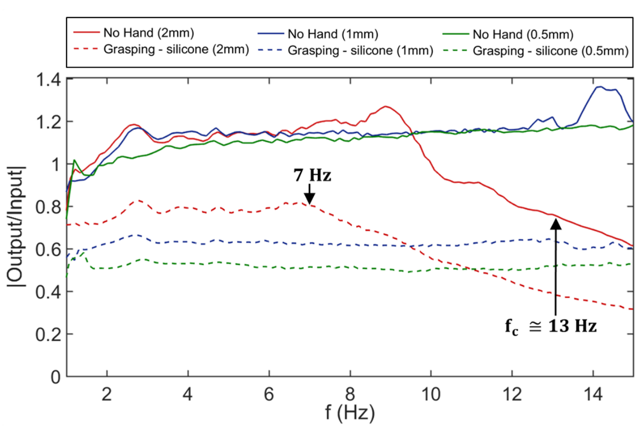

Fig. 5. Bandwidth results obtained through empirical transfer function estimate (ETFE). The corner frequency is at least 13 Hz in all displacement cases without grasping. With grasping, the bandwidth is clearly diminished, with the maximum displacement case worsening after 7 Hz.

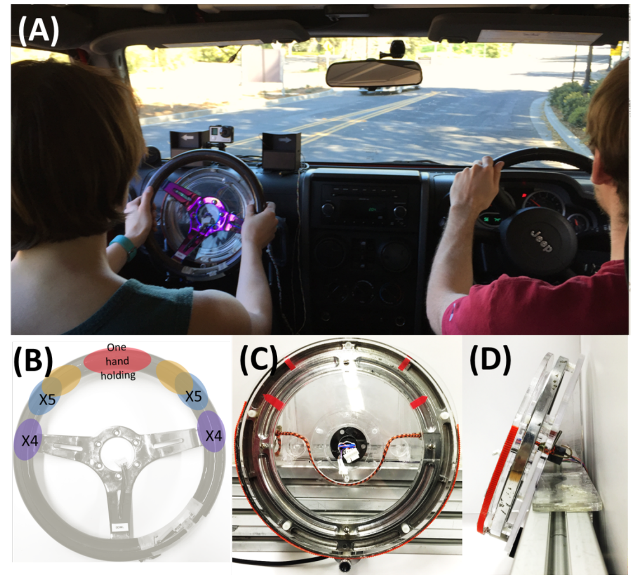

Fig. 6. (A) The haptic steering wheel was mounted on the left side of a right-hand drive Jeep. An experimenter drove on the right while the subject looked through the windshield and completed the experiment. (B) Different steering wheel grips chosen by the users: three chose the purple location only, five chose the blue, one chose the yellow, and one alternated between purple and red. (C) Turntable bearing with elastic cord to provide some turning resistance. (D) Side view of mounting.

2) Bandwidth: To evaluate the bandwidth capabilities of the display, linear chirp position signals were commanded between 1 and 15 Hz over 0.5, 1, and 2 mm displacements, with and without gripping the steering wheel with both hands. A bandwidth of up to 15 Hz was desirable. This is because at higher frequencies it becomes difficult to distinguish directional cues from non-directional vibrations due to the low spatial resolution of Pacinian corpuscles [14], meaning that higher frequencies could be achieved more simply with supplementary vibrotactile actuators. High frequencies may be desirable in future experiments; one idea is to supplement "road feel" by adding high frequency content. As shown in Fig.5, the haptic steering wheel's bandwidth approaches the desired 15 Hz for all cases without grasping. The bandwidth is somewhat diminished when gripped, but is more than sufficient for the directional cues being rendered in this study.

IV. EXPERIMENT SETUP

To create a realistic test environment with significant road vibration and haptic feedback, we used a right hand drive Jeep Wrangler Unlimited. We mounted our haptic steering wheel on the left front dashboard to increase realism for the (North American) participants. An experimenter drove the car while the subject performed the experiment in the left front passenger seat. Subjects were asked to focus on the road and not on the steering wheel as much as possible, but it is a limitation of this experiment that there was no way to enforce this. Future experiments where the subject actually drives while receiving feedback will further increase the realism of the scenario. To mount the steering wheel, we used a large turntable bearing and an elastic cord that allows

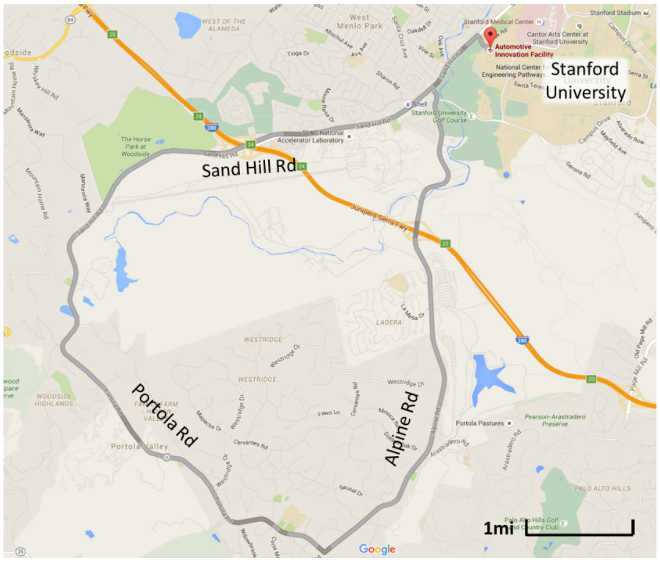

Fig. 7. Car test route marked with gray line on Google Maps image. Total driving distance of one lap is 11.5 miles (18.5 km); driving time was 25 min without traffic. Each subject took at least 2 laps.

subject to turn the steering wheel naturally and feel some resistance and centering torque (Fig.6).

Whenever the vehicle stopped or turned, the experiment was paused and resumed afterward by the second experimenter, so that all trials were performed with the presence of road vibrations and driving distractions. To prevent subjects from receiving auditory cues from the haptic motor, they wore noise-canceling headphones during the experiment.

All experiments were run on the route shown in Fig.7. The route was chosen for the low number of traffic lights, stop signs, and for having low speed limits (usually 35 or 40 mph, with one short section at 50 mph). Attempts were made to stay within the 35-40 mph range as much as possible, and to drive as consistently as possible in terms of speed and handling for every test subject. The road surfaces were primarily smooth concrete.

The subject population consisted of 10 students recruited at Stanford University, composed of 3 females and 7 males, with an average age of 25.5, and average driving experience of 6 years (ranging from 0 to 12 years). Experiments took between 1 and 1.5 hours to conduct, usually consisting of two or three laps of the primary course, and were run at different times throughout the day and evening. Users' hand positions on the wheel were noted. All tests were conducted under IRB Protocol 26526.

V. EXPERIMENT METHODS

Our main experimental goals were to determine whether humans can perceive skin stretch directional stimuli in a moving vehicle and, if so, how large the magnitude and speed of the stimuli must be in comparison to the values found for skin stretch in a stationary environment [16]. We also aimed to determine if they can reliably distinguish between a small selection of different stimuli while in the moving vehicle. This would be useful for assigning more meaning to a stimulus than direction alone. All skin stretch stimuli were of the form shown in Fig. 8.

1) Direction Identification Accuracy Task: We rendered a series of stimuli of different displacements (0.5 mm, 1.0 mm, and 2.5 mm) and speeds (0.5 mm/s, 1.0 mm/s, and 4.0 mm/s), in clockwise (right) and counterclockwise (left) directions, and asked subjects to turn the steering wheel in the direction they felt, making a guess if unsure. The stimuli were chosen to roughly overlap with the higher end of those found useful in [4], as we hypothesized the identification task would be more difficult in a moving car. Each of the 9 possible stimulus combinations was displayed 8 times in random order for each user in both directions, giving a total of 144 stimuli per subject.

2) Absolute Threshold Test: We also ran an absolute threshold test for displacement using the staircase method [21] at two different speeds (1 mm/s and 2 mm/s) as a secondary way of determining how perceivable the stimuli were. In both cases, an initial stimulus of 0.5 mm was displayed to the user. If the user felt the stimulus, which was signified by turning the wheel, the next stimulus would decrease by the step size, which was set to 0.1 mm. If the user did not feel the stimulus, the next stimulus was increased by the step size. This continued until six reversals were achieved, where a reversal is a switch from an increasing next stimulus to a decreasing next stimulus, or vice versa. After six reversals, the step size was reduced to 0.04 mm, and the test was continued until a further six reversals were achieved. The 50% threshold was then defined as the average of the stimulus displacement at the reversals.

3) Task to Distinguish between Small Selection of Stimuli: To determine if subjects could differentiate between a small selection of stimuli, we first chose four stimuli: small displacement right, large displacement right, small displacement left, and large displacement left. The large displacements were 2.5 mm, and the small displacements were 1.0 mm. Given the results of the previous direction identification test, all stimuli were given at 4 mm/s, as we hypothesized that a high speed would make the task easier.

After a short training session, we displayed a randomized series of 40 of these stimuli, and asked participants to reply with which ones they felt while on the road. They replied by turning the wheel by a small angle and back once in the direction they felt for a small displacement and twice in the direction they felt for a large displacement.

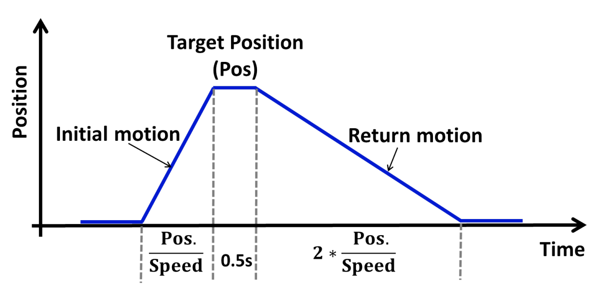

Fig. 8. Standard stimulus trajectory. The displacement of a stimulus is the Target Position shown, and speed is the Initial Motion shown.

VI. RESULTS AND DISCUSSION

1) Direction Identification Accuracy Task: A table of accuracy rates with corresponding 95% confidence intervals (Fig. 9) was created to determine how successful subjects were at perceiving and identifying stimulus directions while in a moving vehicle. Although subjects were asked to always guess what direction they felt, many of the slower and smaller stimuli were imperceptible much of the time, meaning that non-responses were common. Four of the nine stimuli have accuracy rates over 80%, including the 2.5 mm and 4.0 mm/s case, which has a 96% accuracy and the 1.0 mm, 4.0 mm/s case which has a 93% accuracy, confirming that directional stimuli can be perceived in a moving vehicle with sufficient speed and displacement. However, the results are different from those found in a stationary environment, and the displacements and speeds generally need to be higher to be felt with confidence. While [4] was able to achieve above 95% accuracy for stimuli as small as 0.2 mm and as slow as 1.0 mm/s in a stationary environment, we only found comparable accuracy in a moving car at the 2.5 mm, 4.0 mm/s case. This could result from both the driving environment as well as differences in and greater variability of skin contact.

Accuracy seemed to depend heavily on speed, with accuracy for the highest speed never falling below 80%, and accuracy for the lowest speed never rising above 68%. Displacement also clearly had an effect, though not as strongly as speed. Conversely, With the lowest displacement it was still possible to reach 80% accuracy at high speed, and even with the highest displacement, the accuracy fell to 68% at low speed. These effects can be seen more easily in the accuracy rate plots in Fig.10. As with skin stretch in a stationary environment, both speed and displacement are important. However, while in that condition displacement seemed to dominate, in the driving environment it appears that speed is slightly more important.

The reasons for this result need to be explored more, but it seems likely that added vibrations and haptic feedback from the road somewhat mask the displacements, increasing the relative importance of the speed of the feedback motion. It may also be that due to the constant position perturbations felt while driving, humans are constantly taring or re-zeroing their internal perception of the position, making position feedback less clear. These results show that skin stretch displays used in automobiles must be designed to produce larger and faster directional stimuli than those used in other applications, and informs the design of skin stretch displays that will be used for future in-car experiments or commercial production.

2) Absolute Threshold Test: The mean 50% threshold for all participants at 1 mm/s was found to be 0.44 mm, and at 2 mm/s was found to be 0.26 mm. Again, this confirms that the skin stretch is perceivable by subjects, but suggests it is more difficult than in a stationary environment, where accuracy at 1 mm/s and 0.2 mm was over 95%. These results also show the importance of speed, as doubling the speed almost halved the position threshold (p-value 0.021). It should be noted that

Accuracy Rate		Speed (mm/s) 0.5	1.0	4.0
Displacement (mm)	0.5	0.26 (±0.119)	0.42 (±0.118)	0.80 (±0.093)
	1.0	0.44 (±0.134)	0.70 (±0.095)	0.93 (±0.054)
	2.5	0.68 (±0.109)	0.84 (±0.078)	0.96 (±0.032)

Fig. 9. Direction accuracy rate table for all trials of the 10 users, with 95% confidence intervals in parentheses.

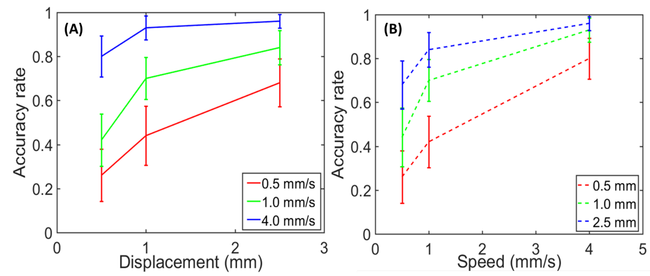

Fig. 10. (A) Accuracy rate trends as a function of stimulus speed. (B) Accuracy rate trends as a function of stimulus displacement.

the stimuli in this test were not manually corrected to remove error from the Hall effect sensor's nonlinear mapping like the stimuli in the other tasks were, due to the large number of stimuli that could possibly be rendered. This may have resulted in a slightly larger position error than the other tasks. It would be worth further characterizing the error in this task and removing it using a better sensor in future work.

3) Task to Distinguish between Small Selection of Stimuli: A confusion matrix was created to analyze how well subjects could distinguish between the four stimuli (Fig. 11) The majority of stimuli, 79.8%, were identified correctly by the subjects, suggesting that it is probably reasonable to teach drivers a small selection of stimuli with assigned meanings for driving tasks. Small displacements were identified with a slightly higher accuracy than large stimuli. There were only four cases of mistaken direction among all trials where subjects perceived left displacements as right displacements. Most of the confusion arose from misidentifying large stimuli as small and vice versa. This further supports the idea that displacement remains important but does not ensure successful identification in the vehicle environment as it did in the stationary environment [16]. The large displacement used here is much bigger than the small, and likely would have been even easier to distinguish in the stationary case. Based on these results and realizing the importance of speed in the direction identification task results above, it seems likely that giving the stimuli different speeds as well as different displacements would make them easier to distinguish and produce less confusion.

VII. CONCLUSIONS AND FUTURE WORK

In this paper we showed that directional skin stretch cues are easily perceivable by the driver if the speed and displacement of the cue are high enough. It was found that the stimuli should be larger and faster than they would

		Actual			
		SL	LL	SR	LR
Answered	SL	**81**	14	0	0
	LL	7	**74**	0	0
	SR	1	1	**86**	12
	LR	1	1	3	**78**
	Missed	0	0	1	0

Fig. 11. Confusion matrix, where stimulus SL corresponds with small left displacement, stimulus LL corresponds with large left displacement, stimulus SR corresponds with small right displacement, and stimulus LR corresponds with large right displacment.

need to be in a stationary environment, and interestingly that stimulus speed was especially important in the driving environment.

Additionally, the 50% position threshold was established at different skin stretch speeds, and it was determined that humans could distinguish between a set of four stimuli of varying direction and position with reasonable accuracy. These results point to the possibility of skin stretch serving as a useful form of feedback in the car, and provide guidance as to how large and fast the stimuli should be to catch the driver's attention.

In future work it would be interesting to run experiments where the subject is able to control the car using the skin stretch steering wheel, so that its benefits can be tested in real driving tasks. Tasks related to haptic previews in autonomous cars, navigation, collision avoidance, and lane keeping are all of interest. A reasonable next step would be to run an experiment in a semi-autonomous car to determine if calmness is actually enhanced by haptic previews. Combination with other feedback modalities also would be useful to look at. One could imagine skin stretch feedback providing subtle anolog cues for initial warnings followed by more intense auditory warnings if the situation becomes urgent. This type of feedback has a high potential to be useful in driving tasks because it provides rich haptic information related to magnitude and direction, it is fast and noticeable, it can render stimuli at a range of frequencies, and it does not steer the car or affect the steering dynamics. In addition, unlike sustained vibratory feedback, it does not lead to desensitization.

VIII. ACKNOWLEDGMENT

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