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SomatosensoryAnticipation of Curvature in a Haptic Virtual Environment

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ABSTRACT

The human visuomotor system uses predictive mechanisms to allow the eye or hand to efficiently follow a moving target. The long-term goal of the present study is to determine whether the somatosensory system has similar capabilities. Subjects used the right arm to move the index fingertip inside of virtual tubes shaped as large elliptical objects positioned in the frontal plane. The virtual ellipses had three different aspect ratios and two different tilts, and some had flattened portions inserted in one of three regions. Each of the 24 virtual shapes was presented only once to each subject, but the subject explored each one by moving in five consecutive laps. Performance was more improved over the laps when subjects were allowed to stay in constant contact with the walls of the tube, rather than attempting to stay off the walls. However, even with this continuous haptic feedback, subjects could not precisely anticipate the timing of an upcoming flattened region. Thus, similar to recent results for visually-guided eye movements, it appears that it is difficult for the haptic guidance system to time the anticipation of an upcoming event.

KEYWORDS:touch, active sensing

INDEX TERMS:H.5.2 [INFORMATION INTERFACES AND PRESENTATION]: User Interfaces---Haptic I/O; J.3 [LIFE AND MEDICAL SCIENCES]: Biology and genetics

1 INTRODUCTION

Little is known about the purely haptic mechanisms that allow humans to explore three-dimensional (3D) surfaces and learnto predict their shapes. Research pertaining to surgical applications is generally focused on the haptic cues that can assist visual control [1, 2] rather than on purely somatosensory guidance mechanisms. Thus few studies have considered haptic exploration without vision, and most of these were restricted to issues of sensitivity or synthesis of features in 2D [3, 4]. 2D haptic studies suggest that subjects tend to bias remembered shapes toward being symmetrical and oriented along cardinal axes [5]. A similar precedence of symmetry is also consistent with the results of a 3D study of visually-guided hand tracking, where predictive mechanisms became engaged when the trajectory of the visual target entered the second half of a symmetric loop [6]. In the present study, we began to explore strategies for use of predictive mechanisms in a purely haptic shape-tracing task.

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2 MATERIALS AND METHODS

Subjects were seated comfortably facing a PHANTOM Premium 3.0 Haptic Device (Sensable Technologies, Inc.) with their right index fingertip strapped into a "finger sled" interface. The subject could move the fingertip freely within a workspace 60.0 cm wide, 60.0 cm high and 30.0 cm deep, unless it encountered a virtual object. The PHANTOM robot was programmed to create real forces on the subject's fingertip that were perpendicular to the surfaces of the virtual object and proportional to distance the fingertip had penetrated the virtual surface. This was accomplished by writing a program in C++ that generated images of geometric shapes (using OpenGL) and enabled subjects to navigate and interact tactilely with those shapes (using the OpenHaptics programming toolkit provided by the device manufacturer).

The virtual shapes used in the experiment consisted of elliptical, tubular objects approximately 40 cm in length along the long axis and 4 cm in diameter (figure 1A), and were positioned in the

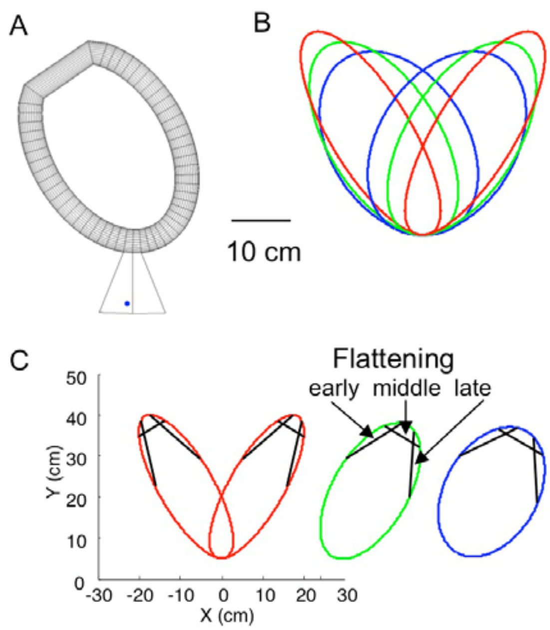

Figure 1. Experimental design. (A) Tubular ellipse (gray) with funnel (pyramid). The blue dot indicates the start position of the subject's fingertip. (B) Ellipses with ratios 3:1, 2:1 and 3:2 of semi-major axis to semi-minor axis (red, green and blue, respectively) were rotated 30 or -30 degrees in the frontal plane. (C) In 18 of the 24 ellipses, a curved section of the ellipse was replaced with a straighttubular segment. Subjects wereinstructed to move clockwise through the shapes, such that the flatteningoccurred at an early, middle or late portion of the shape.

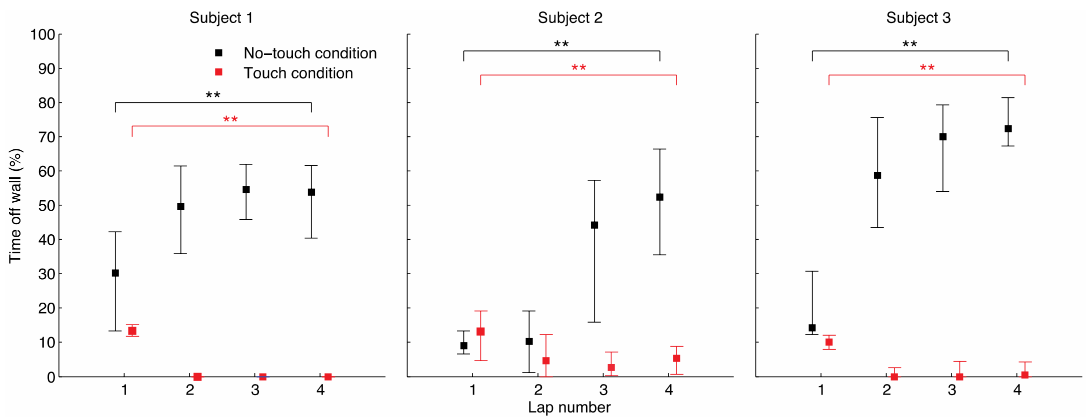

Figure 2. Time off wall relative to lap duration (percentage) for laps 1-4, for the no-touch (black) and touch condition (red). Squares indicate median values over all shapes. Lower and upper error bar represent the 25th and 75th percentile, respectively. Significant differences (Mann-Whitney U-test) between lap 1 and 4 are marked with ** ($p < 0.01$).

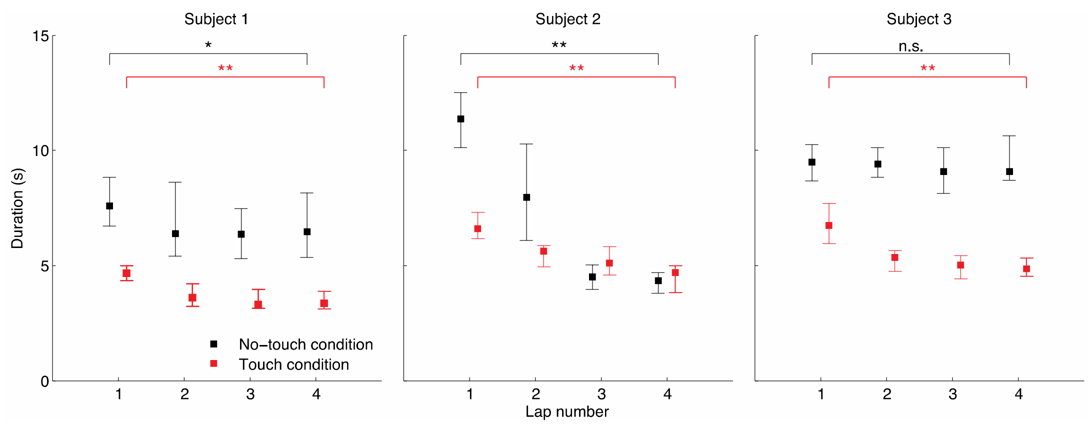

Figure 3. Lap duration in seconds for laps 1-4, for the no-touch (black) and touch condition (red). Squares indicate median values over all shapes. Lower and upper error bar represent the 25th and 75th percentile, respectively. Significant differences (Mann-Whitney U-test) between lap 1 and 4 are marked with * ($p < 0.05$) or ** ($p < 0.01$); differences which are not significant ($p > 0.05$) are marked with 'n.s.'.

frontal plane about 9 cm above the surface of a (real) table positioned in front of the subject. A pyramid-shaped virtual funnel surface was created that extended down below the lowest point of the shape and functioned to guide the subject into the interior space of the object. The virtual funnel extended below the real surface of the table, effectively keeping the subject's fingertip restrained to the inner surface of the funnel, making accidental exploration of the outer surface of the object impossible. The subject started each experimental trial with the fingertip on the table, inside the virtual funnel (blue dot in figure 1A). When the trial started, the subject moved up the funnel and entered the tubular shape, at which time a tone sounded, the funnel disappeared and the hole used for entering the shape was replaced with a solid surface.

The program also recorded position, velocity and force information about the fingertip in 3D at 1 msintervals. For all virtual surfaces, the stiffness was programmed at 1.0 N/mm. The maximum force that the robot could produce is 22 N transiently and 3 N sustained. The maximum force typically used by the subjects on the inner surfaces of the elliptical objects was about 1-2 N.

Three different ratios (3:1, 2:1, and 3:2) of semi-major axis to the semi-minor axis were used in building the ellipses (red, green and blue ellipses in figure 2B respectively). These ellipses were rotated 30 or -30 degrees in the frontal plane (to avoid positioning the shapes along the cardinal axes) and so produced a total of 6 different basic elliptical paths.

In 18 of the 24 ellipses used in the experiment, a curved section of the ellipse was replaced with a straight tubular segment. This was called "flattening" and was calculated to occur at an early, middle or late portion of the shape (figure 1C). This nomenclature is based on the fact that the subjects were instructed to move clockwise through the shapes, and thus the early flattening would be encountered by the subject sooner than the middle or late flattening. (The shape shown in figure 1A depicts middle flattening.) In geometric terms, each flattened section was created by removing 20% of the total coordinate vertices of the shape.

The subjects were normal, healthy adults (1 male and 2 female) and gave informed consent before taking part in the experiment. Each subject participated in 2 experimental conditions consisting of 26 trials each. The subjects used trials 1 and 2 for practice. The 24 remaining shapes represented the 6 basic elliptical paths modified with early, middle, late or no flattening, thus each shape was unique. The sequence of shapes was random but was the same for each experiment and each subject. Trials where subjects moved counterclockwise or machine malfunction was experienced were repeated at the end of the experiment. Subjects did not receive visual information about the shapes presented.

The subject began each trial with the right fingertip at a start position mark on the table and was allowed to rest their elbow on the armrest of the chair. The subject then raised the fingertip into the shape and moved in a clockwise manner around the shape 5 times. After circling the object 4 times, the subject was informed that only one "lap" was remaining. After completing the last lap, the virtual object disappeared, the subject returned the fingertip to the start position and reported whether or not they perceived a flattened region in the shape just explored. Subjects were instructed to remain in constant motion and to keep their eyes closed during the trial.

The “no-touch condition” differed from the “touch condition” in the instructions given to the subjects. During the no-touch condition, subjects were instructed to use the initial laps of each trial to learn the shape and then demonstrate that knowledge by touching the walls of the shape as little as possible. For the touch condition, however, subjects were instructed to move "quickly and smoothly, with as little force as possible against the sides" and to "remain in constant contact with surface of the object." Analysis focused on laps 1-4 due to occasional early termination.

3 Results

The subjects’ performance improved during exploration of the ellipse. In the no-touch condition, where subjects were instructed to stay off the wall, the amount of time that subjects did not touch the inner wall of the ellipse increased for increasing lap number (figure 2, black squares). For all subjects, the percentage of time they stayed off the wall within a lap was significantly larger (Mann-Whitney U-test; $p < 0.01$) for the fourth lap compared to the first lap. However, subjects never touched the wall for less than 20% of the time, and thus they were not completely successful. In the touch condition, where subjects were instructed to trace the ellipse by gently touching the wall, the amount of time that subjects stayed off the wall decreased toward zero after the first lap (figure 2, red squares). The decrease between lap 1 and lap 4 was significant ($p < 0.01$) for all subjects. The values became very close to zero for laps 2-4.

Subjects became faster in exploring the shape in the touch condition. The time subjects spent tracing the fourth lap was significantly shorter ($p < 0.01$) than the first lap (figure 3, red squares), indicating that their average speed increased during tracing of the wall. In the no-touch condition, the duration of lap 4 was significantly shorter than lap 1 for subject 1 ($p = 0.04$) and subject 2 ($p < 0.01$), but not for subject 3 ($p = 0.52$).

We analyzed the responses to the question “Did you detect flattening?” which was asked at the end of each trial. Using the subject reports from all shapes that did contain flattening, figure 4 shows combined data for the three subjects and the two tilts of each ellipse, with each bar representing the average of 6 reports. A score of 100% would mean that in all 6 cases flattening was detected; a score of 0% would mean that the flattening was never detected. Comparing the two experiments (figure 4, left and right), subject reports of flattening were more often correct in the touch condition, when they were allowed to be in constant contact with the walls ($F(1,90) = 6.6$, $p < 0.05$). Reports for the most rounded shape (blue bars) were better than the reports for the longest shape (red bars), with intermediate performance for medium shape (green bars). ANOVA posthoc testing showed that the flattening in the rounded shape was detected significantly better ($p < 0.05$) than for the other two shapes, which were not different from one another (Scheffé test, $p = 0.36$). Flattening was more likely to be detected when it occurred in the middle portion (center bars, horizontal hatching), compared to early and late ($p < 0.01$), but early and late flattenings were not different from one another (Scheffé test, $p = 0.85$). Thus a flattened section was most often detected in the middle of the most rounded ellipse and most often undetected on the sides of the longest ellipse.

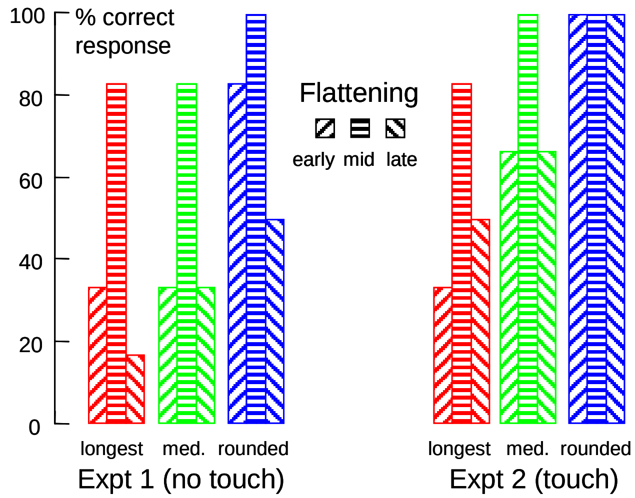

Figure 4. Subject reports of flattening for the no touch (left) and touch condition (right), given in percentage of trials. Red, green and blue bars indicate the average over subjects for the longest (ratio 3:1), medium (ratio 2:1) and rounded (ratio 3:2) ellipses. Early, middle and late flattening are represented by upward diagonal, horizontal and downward diagonal hatching, respectively.

To answer the question about whether subjects anticipate the upcoming flattened section of the shape, or instead merely react after encountering the start of a flattened section, for the touch condition, we analyzed contact force and finger speed around the onset of flattening for the subsequent laps. Figure 5 shows force and speed for subject 3 exploring an ellipse with ratio 3:2 (rounded), tilt = -30 degrees and middle flattening. All subjects reported flattening for this shape (see figure 4). In the first lap (blue), force increased and speed decreased immediately *after*the onset of flattening. This was caused by the subject hitting the “corner” between the smooth section of the ellipse and the flattened section. In the next laps, this peak in force immediately after the onset of flattening was less pronounced. The speed profile *before* the onset differed substantially between the first lap (blue) and the next laps. In the first lap, the speed slightly increased between -1.5 and 0 s. However, in the same time interval the speed decreased for laps 2-4. As a result, the finger speed at the onset of flattening was lower for lap 2-4 compared tolap 1, but higher 1.5 s before the onset. Thus, after exploring the shape for the first time, this subject slowed down before entering the flattened section the next times.

We quantified the instant at which subjects slowed down by determining the cross-over point of the speed trace of lap 4 withthe speed trace of lap 1 (arrow in figure 5), and did the same for lap 3 with lap 1. The analysis required that the speed of lap 1

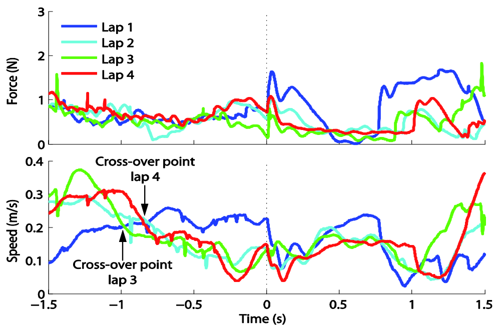

Figure 5. Force (upper panel) and speed (lower panel) for subject 3 exploring an ellipse with ratio 3:2, tilt -30 degrees and middle flattening. Lap 1-4 are shown in blue, cyan, green and red, respectively in Expt 2 (touch). For each lap, the force and speed time traces are aligned to the onset of flattening, which is time zero (dashed line). Arrows indicate cross-over points between the speed trace of that particular lap with the speed trace of lap 1.

remained larger than the speed of laps 3 or 4 between the cross-over point and the onset of flattening. This procedure was repeated for all subjects and for all shapes with a 3:2 ratio and middle flattening. For subjects 1-3, we found a cross-over point in 100%, 100% and 75% of the cases, respectively. The median time instant at which subjects slowed down before the onset of flattening was 343 ms (range 82-613 ms), 270 ms (36-1258 ms) and 245 ms (34-1045 ms) for subjects 1-3, respectively.

4 Discussion

In this study, human subjects explored ellipses by moving their fingertip through a virtual tube. In the no-touch condition, we asked subjects to touch the walls of the tube as little as possible, whereas in the touch condition, subjects were asked to keep contact with the wall while moving smoothly and quickly around the shape. We compared both conditions in terms of performance (force, lap duration and verbal reports of flattening) and we quantified anticipation of flattened sections in the shape.

In the no-touch condition, the time subjects stayed off the wall increased for each subsequent lap (figure 2, black squares). However, subjects never managed to stay off the wall for the whole duration of a lap. This suggests that subjects improved their performance but still had difficulties with anticipating the flattening in the fourth lap. We expected that subjects would move faster if they became better at anticipating the corners. Subject 2 clearly increased his movement speed (figure 3, black squares), but the other subjects exhibited either a slight decrease in lap duration (subject 1) or no decrease at all (subject 3). Therefore, anticipating the corners was rather difficult for the no-touch condition. Most likely, the reason is that since subjects were instructed to stay off the wall and were therefore unable to accumulate haptic information for predicting the shape. In the touch condition, subjects performed well and kept in contact with the wall (figure 2, red squares), which allowed them to accumulate haptic evidence for the shape. Therefore, we expected subjects to become faster over laps in the touch condition, which is what we found (figure 3, red squares).

Another aspect of subjects' performance is whether subjects correctly reported flattening. Scores were higher for the touch condition than for the no-touch condition. We believe that when subjects were allowed to touch the walls, they could actively sense the "corner" between the elliptical section and the flattened section, resulting in higher scores for the touch condition. In the no-touch condition, if subjects succeeded in trying to stay off the wall, they would have tactile information only when they unintentionally hit it.

Middle flattening was more often reported correctly than early and late flattening. Most likely, this is caused by the relatively sharp corners between the elliptical section and flattened section in the middle, compared to the moderate corners found in shapes with early and late flattening (figure 1C). Likewise, the flattening was seldom reported when it was early or late in the longest ellipse. This may be due to the relatively large radius of curvature (about 0.6 m) at the point where the side walls of the long ellipse transitioned into the flat region. A previous 2D study, using a psychophysical technique, showed that subjects perceived a radius of curvature of about 2 m as being straight [3]. Thus the transition between the gently curved sides of the long ellipse and the early and late flat regions may have been indistinct.

In designing the experiment wedecided we should not orient the elliptical shapes along the cardinal directions [5]; thus the shapes were relatively difficult for subjects to recognize and remember. Performance was better when subjects were allowed to stay in contact with the wall and they did show some evidence that they anticipated approaching an upcoming flattened region (figure 5). However, this anticipation was not particularly consistent or precise. In our analysis of the shape with the most obvious flattening (the rounded ellipse with the middle flattening), the three subjectsdid show anticipation,but the timing varied widely even within an individual subject, ranging from about 100-1000 ms prior to the event. This lack of precision in anticipation is reminiscent of the results of recent studies of smooth pursuit eye movements, where shape cues were of little use unless they could be coupled to timing mechanisms [7,8]. Potential mechanisms for extrapolation of somatosensory targets, such as gradual or familiar surface shape transitions, have yet to be explored.

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