CURVATURE DISCONTINUITIES DISCRIMINATION DURING DYNAMIC EXPLORATION OF SURFACES

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Abstract

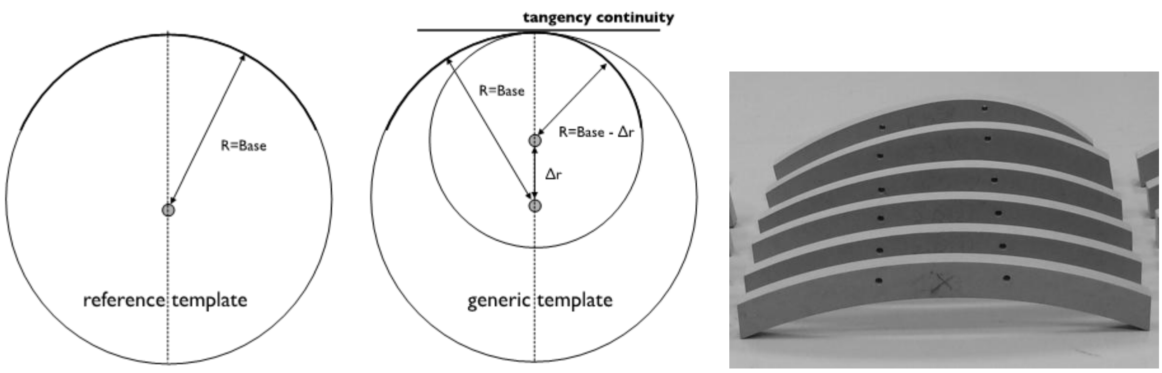
We conducted a two alternative forced choice discrimination experiment to evaluate subjects' capability of perceiving curvature discontinuities during a dynamic exploration task. Five 500 mm long templates were milled with different degrees of discontinuity. Discontinuities were geometrically obtained by varying the curvature radius (base radius) by Δr *, while maintaining continuity in tangency in the middle point. On each trial we asked 20 participants to distinguish between a reference continuous curved stimulus and a discontinuous one. Results showed that subjects were able to distinguish the discontinuous stimulus from the continuous one when occurred a variation of the base radius around* 24% *or more. Moreover, we tracked the hand's movements during the stimuli exploration, and correlated the dynamic aspects of the explorations with the proportion of correct response for each level of the stimuli. Results led us to hypothesize that dynamic cues could play a role in curvature discontinuity discrimination.*

The human ability to perceive the shapes of the objects interested the experts of perception since the first days of the psychophysics. In particular, the ability of recognizing different curved surfaces by touch is a relevant topic in those virtual reality systems that implements haptic feedback. Indeed, several different systems have been made to simulate curvature in the virtual world (Bordegoni et al., 2010, Frisoli et al., 2008) making the users able to touch a virtual curved surface as it was real**.** Thus, a series of studies have been performed in the engineering and psychophysical fields to better understand human ability to perceive curvature. For example in (Pont, Kappers, & Koenderink, 1997) it has been evaluated the subjects' capability to discriminate curvatures that are statically touched with different regions of the hand. Authors demonstrate that the cutaneous stimulation is an important factor in the human capability of discriminating surface, depending on the distribution of receptors on the hand skin and also on the contact length. In the same work they conclude that the effective stimulus for the discrimination of curved strips is the total difference in local surface attitude. In (Pont, 1997) the author replicates this finding also with an active dynamic touch paradigm, in accordance with the classical results obtained by Gordon and Morrison in (Gordon & Morison, 1982). In the works described in (Louw, Kappers, & Koenderink, 2000, 2002) participants were asked to detect or discriminate Gaussian profiles through dynamic exploration. It is demonstrated that the discrimination threshold increases with a power of 1.3 with the width of the shape. In van der Horst & Kappers (2007) it is examined the curvature discrimination aspects connected with the exploration procedure. In these studies it is found that the way of exploration has a remarkable effect on the discrimination performance of the subjects. In a following study (van der Horst & Kappers 2008) it is also found the presence of a complete aftereffect transfer between the two hands. Finally Wijntjes et al. (2009) replicated the studies of Pont et al. with a dynamic exploration paradigm. Their results point out that the curvature of a given surface can be expressed by four different descriptors, that are: changes in height, curvature, total orientation changes and the length of the path of exploration. It is demonstrated that for a given length of exploration path (from 12 to 780 mm) the total orientation changes are the dominant cues to understand the curvature of a given surface**.**

In the present work a different question is addressed, which is the minimum discontinuity in a curved surface that can be detected by subjects through dynamic exploration. It is also examine the trajectory of the subjects' hand during the exploration, in order evidence the role of the dynamic cues in the curvature discontinuity discrimination.

Method

Twenty right-handed participants (5 females and 15 males) aged between 19 and 32 with no known neuromuscular disorders and naive to the task, participated in the experiment. All participants gave their consent prior to testing. The experimental setup consisted in a series of curved templates presenting discontinuity in curvatures, milled using a numerical controlled machine and mounted on a wooden plane having two metal rails in which the stimuli were inserted by means of two holes symmetric with respect to the middle plane (Figure 2a). All the templates have been geometrically defined by varying the value of a given radius of curvature subtracting a Δr (G2 discontinuity), while maintaining continuity in tangency (G1 continuity) in the middle point (as illustrated in Figure 1). The standard stimulus (without discontinuities) was an arc of circumference of 540 mm long. The circumference had a 800 mm long radius. The variation of this base radius for the test stimuli was, for the first four subjects, a variation of 0%, 10%, 25%, 40% and 55% of the base radius. Given the high probability of correct response for the last two stimuli the set of possible variations has been changed in order to obtain a more precise threshold estimation. Thus, from the fifth subject to the twentieth, the variations of the base radius was equal to 0%, 5%, 10%, 25% and 40%. The null variation of 0% has been introduced to check for possible biases in the presentation order of templates.



(a) (b) (c)

Fig. 1. Two templates obtained varying the curvature radius keeping the tangency constant. In the left image (a) there is a continuity of the curvature radius. In order to obtain a discontinuity in curvature we only introduced a variation of the value of the radius while keeping the two tangents parallel (b). In the right image (c) some curved templates.

Participants at the experiments seated comfortably on a chair, in front of a table where the wooden plane was insured. The height and position of the chair were adjusted so as to align the right elbow with the center of the workspace. The order of the standard and the test stimuli on the plane (first vs. second) was balanced and randomized between trials. On each trial the subject started to explore the first template presented. When the subject was ready to start the exploration of the second template, the stimulus was changed by the experimenter. Subject task was to detect the template between the two presented on each trial that presented a variation in the curvature radius. A 2AFC paradigm has been adopted. A brief familiarization period was offered at the beginning of the experiment (26 trials, only using the two steepest stimuli as test stimuli). After the familiarization, participants were blindfolded, in order to prevent all the visual cues. Experiment lasted one single session having 100 trials (5 test stimuli 2 presentation conditions X 10 repetitions). The evolution of the curvature (steeper side of the stimulus leftward or rightward) was changed every 10 trials.

Threshold estimation

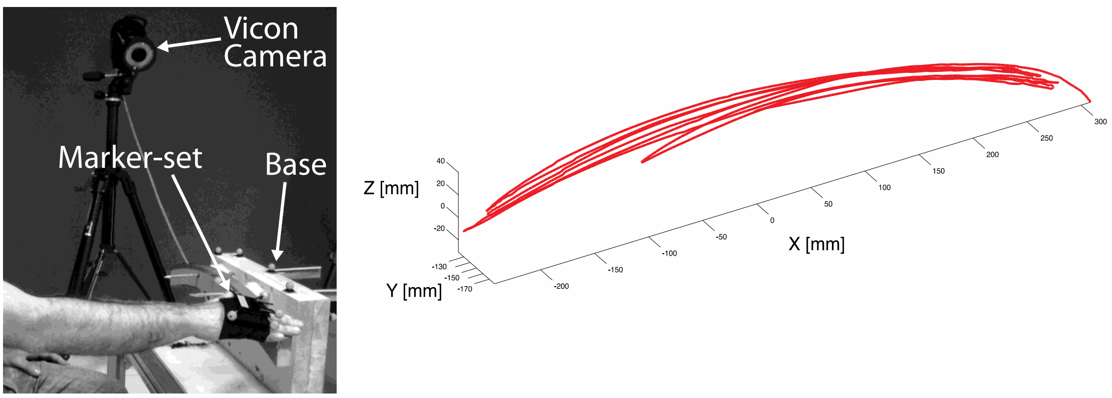
For each participant, a stimulus response matrix for each Δr was constructed and the sensitivity index d' and response bias β were calculated (Macmillan & Creelman, 2004). In order to estimate the absolute thresholds in the curvature surface continuity we computed the slope of the best fitting line by averaging the slopes (α) of the d' corresponding to the four $\Delta r\%$. α was computed as:

$$\alpha = \frac{\left(\frac{d'_1}{\Delta r\%} + \frac{d'_2}{\Delta r\%} + \frac{d'_3}{\Delta r\%} + \frac{d'_4}{\Delta r\%}\right)}{n}$$

Where n is the number of test stimuli and d'_i, the sensitivity index for the discrimination between standard and test stimuli, was divided by the respective $\Delta r\%$. The threshold was then calculated as1/α, which corresponded to the $\Delta r\%$ for $d' = 1$ (see (Pang, Tan, & Durlach, 1991)).

Hand trajectory recording.

During the test, we also recorded the position of the user hand in the space by means of an optical tracking system. For this purpose we used a Vicon System (www.vicon.com) equipped with 5 cameras (model M2) and two marker-set for the tracking of the hand and the base. The cameras sensor works only in the infrared spectrum. The system detects and tracks reflective spheres of 14 mm, which are illuminated by IR-sources with a frame rate of 120 Hz. We positioned the cameras in order to cover the entire working volume for the test (850 mm x 650 mm x 600 mm). The measurement error was under the millimeter. During the test the user wears a marker-set on the back of the hand and explores freely the surface, while the system detects the position of the hand relative to the base (Figure 2a).



(a) (b)

Fig. 2. The recording of hand movement. In the left image (a) the whole tracking system for the experiment is shown. In the right image (b) an example of the recorded data during a test.

We processed the recorded data in order to obtain a compact representation by considering only one describing dimension. Actually, we discarded the movements in orthogonal direction to the template, because limited by its thickness. Subsequently, we computed the curvilinear abscissa related to the curve. The hand position on the curvilinear abscissa has been exploited to estimate the kinematic features. We applied a low pass filter working at 4 Hz to the data and then speed, acceleration and jerk of the movement have been computed by means of numerical differentiation. Finally, we computed point-biserial correlation index (r^2_{pbis}) to correlate the obtained dynamic features with the correct responses for the stimuli that were around the estimated thresholds.

Results and Discussion

Threshold estimation

We computed the curvature discontinuity thresholds for all participants with respect to the base radius both fitting the best fit line to the averaged subjects d' and averaging the individual thresholds for each subject (results shown in Table 1). Results for the subjects 7, 9 and 16 has been omitted, since in these cases there was a too high rate of missing and false alarms that makes us unable to estimate the thresholds. However, for the remaining subjects the estimated variation of the radius of curvature necessary to feel a discontinuity on the surface and necessary to discriminate a discontinue surface from a continue one for a base radius of 800 mm was 24.8% of the radius itself (pooled d'). Moreover, the threshold from each single subject results (indicated as mean ± standard error of the mean) was 26.66% ±9.3%. The presence of response bias due to the order of presentation of the stimuli has been also tested, computing the frequency of responses in which the subject indicated the stimulus with discontinuity presented as first on the wooden plane when the two stimuli were identical and with a continuous curvature ($\Delta r\% = 0$). The participants' frequencies of responses at 90 % binomial interval of confidence (from 8 to 14 for N=20 and p=0.5) did not exhibit a response bias. We also examined whether the proportion of correct response (hit) varied together with the evolution of the curvature. A paired t-test at 95% confidence interval revealed no difference between the participants' proportion of correct response with respect to the side of the evolution (t=0.31, p=0.77). In order to perform this test only the response at stimuli with the $\Delta r\%$ near to the single subject's threshold has been used, excluding the Δr% with a proportion of correct responses > 80% or < 65%.

The threshold values are in line with the results exposed in the studies previously cited despite a quite large variability between subjects. In fact, it is possible to see the subjects task as a comparison between two different tilted and adjacent 250mm long curvature, the first one with a 800 mm long radius, the second one with a smaller radius and symmetrically displayed. From this point of view, basing on the study of Wijntjes et al. (2009), the main cue for the curvature discrimination (and then for feel discontinuity in two surfaces with a constant tangency) for 250 mm long stimuli is the local surface orientation (attitude).However, the G1 continuity between the two shapes with different curvature and the possibility to explore them with a whole continue movement is a core difference between our and the previous studies. Thus, in order to test whether some aspect of the exploration is connected to a better or worse discontinuity perception we tracked the participants' hand movements and the movement features have been correlated with the occurrence of correct responses.

Subject	Threshold (%)	Acc. mean (r^2_{pbis})	Dec.mean (r^2_{pbis})	Acc.peak (r^2_{pbis})	Dec.peak (r^2_{pbis})	Velocity mean (r^2_{pbis})	Velocity peak (r^2_{pbis})	Jerck mean (r^2_{pbis})	Jerck peak (r^2_{pbis})
1	24	-	-	-	-	-	-	-	-
2	11.6	-	-	-	-	-	-	-	-
3	9.6	-	-	-	-	-	-	-	-
4	13.9	-	-	-	-	-	-	-	-
5	16.5	0.24	-0.45*	0.08	-0.04	0.01	0.42	0.14	0.19
6	19	0.35	-0.39	0.45*	-0.32	0.5	0.48*	0.48*	0.32
8	14.7	0.28	-0.10	0.21	0.11	0.01	0.06	0.18	0.23
10	18.2	0.30	-0.33	0.48*	-0.24	0.49*	0.54*	0.23	0.26
11	38.3	0.27	-0.41	0.15	-0.30	0.21	-0.29	0.26	0.24
12	15.8	-0.05	0.04	-0.34	0.16	0.16	0.26	0.01	0.05
13	10.6	0.53*	-0.68*	0.34	-0.49*	0.69*	0.67*	0.65*	0.41*
14	13.3	0.38	-0.38	0.10	-0.27	0.35	0.20	0.39	0.19
15	12.3	0.70*	-0.57*	0.59*	-0.11	0.72*	0.76*	0.57*	0.41*
17	20.7	0.21	-0.30	0.13	-0.22	0.17	0.21	0.03	0.16
18	37	0.34	-0.48*	0.40	-0.12	0.59*	0.46*	0.59*	0.49*
19	16.2	0.30	-0.29	0.04	-0.27	0.08	0.06	0.09	0.01
20	12.9	0.07	-0.09	0.13	-0.08	0.16	0.06	0.07	0.15
Pooled	24.8	0.23*	-0.25*	0.18*	0.14*	0.28*	0.22*	0.24*	0.15*
Mean±sd	26.6 ±9.3								

Table 1: Result reported for each subject. Point-biserial correlation coefficients are showed for the dynamic aspects of the movements taken in account, significant correlation ($p < 0.05$) are marked with *. Data are reported for single subject and pooled data.

Trajectory analysis

We tracked and analyzed the exploration path for 13 out of 20 subjects during each trial. Among the recorded trajectories we selected those performed on the discontinuous stimulus that was nearest to the threshold (meaningful paths). Subsequently we computed the point-biserial correlation for each of the 13 subjects, correlating the number of correct response respectively with: the mean of acceleration, deceleration, velocity and the jerk in a single trial, and the amplitude of the peak of acceleration, deceleration, velocity and jerk during the single trial. Results for each subject are shown in Table 1. We also evaluated the just cited correlation pooling together meaningful paths. The results are also shown in Table 1.

Weak statistically significant correlations have been found for all the dynamic aspects of the exploration considering the pooled data. Despite the correlations for pooled data are not very high, it is important to note that all data came from a free exploration task. In particular for five subjects out of 13 the dynamic cues have a medium- high correlation (from 0.45 to 0.7) with the occurrence of correct responses. This led us to guess the existence of an additional cue given by the active shape exploration. Basing on the evidence that the velocity is the highly correlated features also for pooled data, we hypothesize that this additional cue could be how fast the local orientation varies among the subject movement.

The perception of this variation could be enhanced by a faster exploration of the surface. To test this hypothesis a paradigm for a further experiment in which the velocity of the local surface changes may be controlled sliding the templates under the subject hand while he is performing the task has been thought.

Conclusion

The aim of the current study was to evaluate the subjects' capability to discriminate a continuously curved surface from a discontinue one that was obtained varying the radius of curvature of a continuous reference surface by a given $\Delta r\%$. Our results based on the SDT theory showed that the minimum variation in the radius necessary to make the subjects able to detect a discontinuity in the surface curvature was roughly a variation of 25% of the base radius. We also evaluated the importance of the dynamic aspect of the exploration in the subjects' capability to perceive the discontinuity. Basing on the point-biserial correlation calculated between dynamic features and occurrence of correct response we speculate that the velocity of exploration could have a role in the perception of discontinuity in a curved surface, but further direct studies are necessary to prove this hypothesis.

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