Multimodal Curvature Discrimination of 3D Objects

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Abstract

As virtual reality technologies are advanced rapidly, how to render 3D objects across modalities is becoming an important issue. This study is therefore aimed to investigate human discriminability on the curvature of 3D polygonal surfaces with focusing on the vision and touch senses because they are most dominant when explore 3D shapes. For the study, we designed a psychophysical experiment using signal detection theory to determine curvature discrimination for three conditions: haptic only, visual only, and both haptic and visual. The results show that there is no statistically significant difference among the conditions although the threshold in the haptic condition is the lowest. The results also indicate that rendering using both visual and haptic channels could degrade the performance of discrimination on a 3D global shape. These results must be considered when a multimodal rendering system is designed in near future.

Keywords : 3D curvature discrimination, visual and haptic perception, 3D multimodal rendering, psychophysics

I. Introduction

Humans recognize objects by using geometric properties, such as edges, angles, and curves. Although all are important factors to determine the shape of objects, curvature provides more clues (e.g. illumination effects, shape details) that help humans with shape perception. For this reason, researchers have studied curvature discrimination with either haptic or visual modalities [1, 2, 3].

Frisoli et al. [1] has conducted the most recent study on haptic curvature discrimination, where they investigated the effects of providing kinesthetic (force) cues versus providing both kinesthetic and cutaneous (contact orientation) cues. From their study, the authors conclude that providing both kinesthetic and cutaneous cues improve curvature discrimination ($1.51 \pm 0.2\ m^{-1}$ vs. $2.62 \pm 0.61\ m^{-1}$). However, the authors did not investigate the effects of using both visual and haptic cues for curvature discrimination.

As an initial study for 3D global shape discrimination with two sensory channels (vision and touch), Kim et. al. [4] has employed three simple deformations (compressing, shearing, stretching) to measure the discriminability on 3D global shapes. The results indicated that vision was more sensitive than touch and even using both channels at the same time was better than using haptic channel only. As a most recent study, Philips et. al [5] examined the visual and haptic perception of 3D shapes by using feelies and bell peppers.

To the best of our knowledge, no existing study has studied curvature discrimination using both haptic and visual modalities. Therefore, we designed a psychophysical experiment using signal detection theory to determine curvature discrimination for the following three conditions: haptic only, visual only, and both haptic and visual. Before proceeding with the study, we initially believed that curvature discrimination in the visual condition would be better than curvature discrimination in the haptic condition because vision is more sensitive to low-frequency variation [6]. However, our conclusions did not yield any statistically significant difference between the conditions. Possible reasons include insufficient number of subjects and learning effects. While statistical analyses did not provide much insight, the results do suggest that providing both haptic and visual cues distract subjects and results in degraded

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performance from their preferred sensory modality (i.e. the modality that achieved the lowest curvature discrimination). This result can be confirmed in future studies where learning effects are reduced.

II. Methods

Fig. 1. OMEGA3 haptic device

A. Apparatus

To test the haptic modality, an OMEGA device that provides force-feedback (stiffness 14.5 N/mm) is used. This device provides very high position resolution (10 micrometer) in three-dimensional space (i.e. 3 degrees of freedom) via the knob as seen in Figure 1. A standard PC monitor (1280 by 1024 pixels) is used for the visual display, and a keyboard is used by the participant to enter his/her response.

B. Participants

Three subjects (two males one female), aged from 30 to 34, participated in the experiments. All are right handed and have no visual (with the exception of corrective lenses) or haptic impairments. All of the subjects had ever no experience with haptics devices.

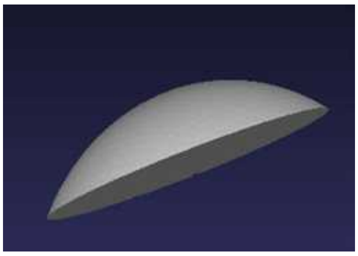

Fig. 2. An example of a 3D curvature

C. Stimuli

A test stimulus is defined as a curvature (*k*) equal to the inverse radius (r^{-1}) of a sphere, i.e. k=1/r. For simplicity, a curvature is generated by cropping a circular portion of the sphere. To avoid edge effects at judgement, all curvatures have the same circular base, where the radius of the base is 0.08 m. An example of a 3D curvature is shown in Figure 2.

	$k_1(m^{-1})$	$k_2(m^{-1})$	$\triangle k(m^{-1})$
Small $\triangle k$	4.00	4.50	0.50
Medium $\triangle k$	4.00	5.00	1.00
Large $\triangle k$	4.00	5.99	1.99

Table 1. Curvatures presented for each series

To determine curvature discrimination, three series with different $\triangle k$ (small, medium and large curvature differences) are used (Table 1). As $\triangle k$ increases, the ability to discriminate between the curvatures are expected to increase (i.e. the task becomes easier as $\triangle k$ increases).

D. Procedures and Experimental Conditions

There are three experimental conditions: (H) haptic only; (V) visual only; and (HV) haptic and visual. Each subject follows the same sequence of conditions, beginning with HV, followed by V, and ending with H. This particular sequence was chosen with the intent of reducing user fatigue by separating the conditions that require the haptic device.

For each condition, 100 trials of each series(small $\triangle k$, medium $\triangle k$, or large $\triangle k$) are presented. This results in 300 trials for a given condition and 900 total trials for each subject. To reduce learning effects, the order in which the series are presented are randomized and unknown to the subject until a given series begins. On each trial, two curvatures are presented temporally (with no time limit) and the subject is asked to respond to the question, “Which curvature is more curved?” At the start of each trial, the first stimulus is presented, and when the subject is ready, he/she presses the “Page Down” button to proceed to the second stimulus. The subject then responds by pressing “1” on the keyboard if curvature 1 is more curved or “2” if curvature 2 is more curved. After responding, the subject is provided with feedback about his/her response (i.e. correct or wrong). For each trial, the order in which the curvatures are presented is also randomized.

During each experiment, the subject sits at a desk where the haptic device, computer monitor, and keyboard are placed. For the haptic only condition, the monitor is blocked from the subject with a curtain and only the haptic device is used to make a judgment; the experimenter notifies the subject when he/she should begin and provides feedback to reset haptic device positioning after his/her response. For the visual only condition, the haptic device is not used and curvatures are displayed on the monitor. For the visual and haptic condition, both the haptic device and monitor are used (Figure 3). All subjects participate in a practice session (4 trials per series) for each condition prior to the start of the actual trials.

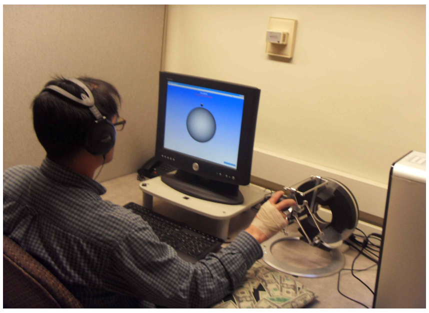

Fig. 3. Experimental setup

E. Data Analysis

Signal detection theory for a 2-interval experiment (also known as two-alternative forced choice, 2AFC) is used to analyze the results[2]. Let $U_1 = (S_2, S_1)$ and $U_2 = (S_1, S_2)$, where S2 represents the stimulus that is more curved. Then R1 corresponds to the response that the first stimulus presented is more curved and R2 corresponds to the response that the second stimulus presented is more curved. The resulting response matrix is shown in Table 2. As mentioned earlier, the sequence in which the stimuli are presented is randomized over the trials.

For a given series, it is possible to obtain the sensitivity index, d' using the hit(H) and false alarm (F) rates. Assuming that a subject's response given a particular sequence is normally distributed, then the sensitivity index for a 2-interval experiment is calculated as follows:

	R_1	R_2
U_1	Correction Rejection	False Alarm
U_2	Miss	Hit

Table 2. Response matrix (Note that U and R represent stimuli and responses, respectively)

$$d' = \frac{z(H) - z(F)}{\sqrt{2}} \tag{1}$$

where z(H) is the z-value of Standard Normal Z Table corresponding to the hit rate and z(F) is the z-value corresponding to the false alarm rate [7].

After obtaining sensitivity indices for a particular subject, is plotted versus Δκ for each condition. A line is fitted through the $(\triangle k,\ d')$ pairs and the just-noticeable difference (JND) is the inverse slope of the fitted line. (Note that JND is equivalent to a subject's discrimination threshold for a given condition.) An example plot illustrating the results for subjects is shown in Figure 4.

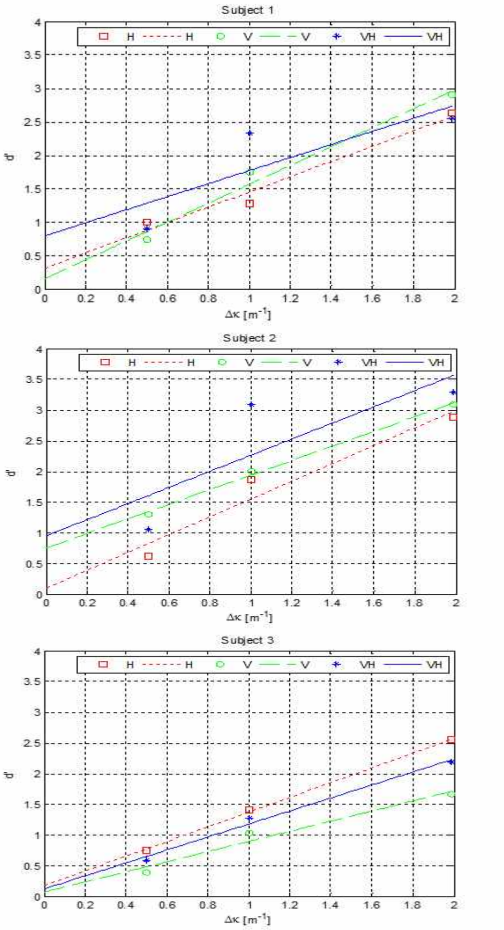

Fig. 4. Results for subject 1, 2, 3

III. Results

JND values for all subjects across all conditions are shown in Table 3. A cursory investigation of the results indicates that there is a considerable degree of variability in subject performance across the conditions. For example, subject 1's ability to discriminate was best in the visual condition, while subjects 2 and 3 were best in the haptic condition. However, statistically, the average JND values across the conditions do not appear to be significantly different from one another. This is confirmed with ANOVA ($p = 0.6753$) and multiple comparisons of the means using the Tukey test. As a result, it is not possible to discern statistically whether curvature discrimination is better in one condition as opposed to another.

	$JND_H[m^{-1}]$	$JND_V[m^{-1}]$	$JND_{HVHV}[m^{-1}]$
Subject 1	0.8771	0.7086	1.0242
Subject 2	0.6903	0.8429	0.7611
Subject 3	0.8337	1.2120	0.9451
Avrg.	0.8004	0.9212	0.9101
Stnd. Dev.	0.0978	0.2607	0.1350

Table 3. JND values for all subjects

Janson [8]	Frisoli [1]	Our result
$1.1\ m^{-1}$	$1.51 \pm 0.2\ m^{-1}$ & $2.62 \pm 0.61\ m^{-1}$	$0.8 \pm 0.098\ m^{-1}$

Table 4. Comparison of curvature discrimination thresholds

A closer inspection of the individual results does suggest a couple of interesting trends. First, JND values in the HV condition are larger than those in the haptic condition for all subjects. They are also larger than the JND values for each subject's best single modal discrimination (Subject 1: visual, Subject 2: haptic, and Subject 3: haptic). It appears that the presentation of both cues may have created a distraction, and thus, degraded performance.

However, learning effects may have also played a role the HV condition was presented first for all subjects. Further studies that reduce this learning effect (by randomizing the conditions) can confirm our hypothesis.

Second, the standard deviation in the haptic condition is smallest of the three conditions, where average JNDH=0.92 ± 0.098 m^{-1}. This implies that the haptic condition may be a more reliable modality for curvature discrimination.

Lastly, it is important to note that subject 2's JND values are noticeably smaller than subjects 1 and 3 for the conditions requiring the haptic device. This is most likely due to subject 2's prior experience with the haptic device.

IV. Discussion and Conclusions

Comparing our haptic condition results with those in literature (see Table 3), our result with a reference curvature of $4.0m^{-1}$ is better than those reported by Frisoli [1]. Our result is also better than those concluded by Jansson[8], where curvature discrimination is reported as 1.1 m^{-1} (cited by Frisoli [1]). One possible reason for this outcome may be that the haptic cue provided by the OMEGA is more informative, although this needs to be further investigated. Another possible reason includes the selection of $\triangle k'$s (which is also mentioned later in the discussion), resulting in very high d′ values and lowering our JND estimates. Future studies must address a more careful selection of before any conclusive results can be made.

As mentioned before, there is no statistically significant difference in curvature discrimination across the conditions tested in this experiment, which is somewhat surprising. Based on initial assessments, we believed that curvature discrimination for the visual condition would be better than the haptic condition. However, with only 3 subjects and considerable variability performance amongst them, we were unable to conclude this statistically. Future studies to use additional subjects in order to obtain statistically meaningful results.

There are additional limitations to our study that must be mentioned. First, it appears that there may be a learning effect as the trials continue, particularly when using the haptic device. Subjects noted that it became easier to use the haptic device after more exposure to it. To reduce learning effects, it may be necessary to randomize (and balance) the sequence in which the conditions are presented to the subjects.

Second, careful selection of $\Delta\kappa$'s may be necessary. For subjects 1 and 3, may have been too easy, where .This is attributed to a few instances where the false alarm rate was 0 % or the hit rate was 100 % (for subject 2, one series had both 0 % false alarm rate and 100 % hit rate). The effects of the large values is clearly discernable when generating the plots. Large values introduce errors when fitting a line through the data, resulting in an inaccurate JND estimate. This is particularly true when a supposedly medium-difficulty task results in a large value.

Lastly, a lack of consistent curvature rendering times among the conditions may have also played a role in performance. For conditions requiring the haptic device, it takes longer to render the curvatures. Since this delay is not present for the visual only condition (since the haptic device is not required), it may have affected performance. Future studies may want to force a delay in displaying the curvatures to match rendering time when the haptic device is required. This can eliminate one factor.

Our study suggests that designers or developers who will work for multimodal rendering systems must carefully consider both vision and haptic channels to render 3D shapes with varying curvatures. The thresholds from the present study can also potentially be used as the upper limits for selecting data hiding strengths (watermark strengths) in order to ensure watermark imperceptibility in a 3D visuohaptic watermarking.

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