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Haptic Shape Discrimination in Virtual Environments Using Force Direction

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ABSTRACT

Shape discrimination of objects relies on sensory and contextual cues. While existing studies explored cues for shape discrimination, an underexplored question remains what the minimal haptic cue (one kind of the sensory cues) is sufficient for such discrimination with contextual cues in virtual environments (VE). This study examined whether the changes of force direction – as a haptic cue – could serve this sufficiency. The results of the study confirmed the sufficiency for the discrimination under certain conditions. This confirmation implied a potential of applying force direction to simplify the design of haptic cues for VE applications.

Keywords: virtual environments, shape discrimination, force cues.

Index Terms: Human-centered computing ~ Human computer interaction (HCI) ~ Interaction paradigms ~ Virtual reality

1 INTRODUCTION

In virtual environments (VE), haptic discrimination of object shape depends on sensory cues (e.g., haptic and visual) and contextual cues (e.g., algorithmic errors) [1]. Existing efforts have examined the effect of different sensory and contextual cues on haptic shape discrimination [2, 5]. While differentiating certain characteristics among various objects, shape discrimination is generally a comparative and complex process. However, one underexplored question is: what is the minimal sensory cue required for haptic shape discrimination in VE under contextual cues (algorithmic errors)? Answers to this question could serve to reduce design complexity of virtual objects while preserving haptic realism even involving potential algorithmic errors.

Integrating haptic cues (like force) with visual cues (such as object geometry) is essential for facilitating user experiences in VE. Haptic cues are important for shape discrimination of objects, especially when visual cues are compromised. Haptic shape discrimination of such objects involves sensing force and geometric cues. Human users can discriminate object shape through force – i.e., its direction and magnitude – without evoking visual cues of object geometry [5]. Moreover, force direction could permit the users to discriminate objects [2]. Thus, this study investigated the sufficiency of changing force direction (a sensory cue) for haptic shape discrimination under algorithmic errors in VE.

2 METHODS

Study Design: With an ethical approval of our institute, the study had 12 participants in imbalanced genders (3 females and 9 males; 26.3 ± 4.66 years old). This imbalance would have no gender-based effect on shape discrimination of abstractive objects [manuscript in preparation]. Pre-test screening confirmed all participants to be right-handed, with normal or corrected-to-normal vision, VE

experienced, and without touch impairments. Each participant provided an informed consent prior to being involved in the study.

Running on a Dell Precision T5820 computer (Windows 10), a VE was created using Unity3D (2019.4.32f1) and interacted via a haptic device (Omni, 3D Systems). As depicted in Fig. 1, each participant used an Oculus Quest 2 headset and held the stylus of the device in the right hand for interaction. The visual scene of this VE displayed on the headset was a helicopter cockpit, which allowed the participant – acting as a firefighting helicopter pilot – to see a lake, mountains, and burning trees.

The participant used the stylus of the haptic device to perform 3 actions: scooping water, dropping water, and flying. Mimicking the "collective" controller of the cockpit, the stylus delivered force cues to the participant's hand to actuate the flying altitude of the helicopter while it moved towards (or over) the mountains and burning trees. Engaged in a quasi-practical scenario of firefighting, the participant's actions were like discriminating an invisible surface by relying on haptic cues without viewing this surface. Scooping water needed the participant to descend the helicopter, collect water (a load) into a bucket under the helicopter (i.e., the participant could not see this bucket), and ascend the helicopter to its flying altitude. This action was like coursing a Gaussian valley as indicated in Fig. 2(a). Dropping water caused the helicopter to ascend in the air because of losing the load and, in turn, the participant required to descend the helicopter back to its flying altitude. Hence, this action was like traversing a Gaussian ridge as shown in Fig. 2(b). Flying (none) was to maintain the helicopter's path at the same altitude, comparable to traversing a flat surface as depicted in Fig. 2(c). Respectively, the 3 actions could be mapped

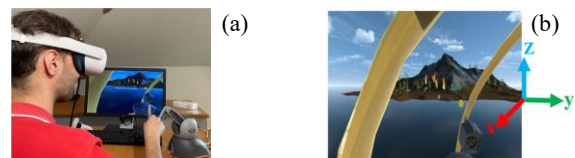


Figure 1: Study setting: (a) the VE setup with a participant wearing an Oculus Quest 2 headset, a monitor, and a haptic device (Omni); and (b) the view of the visual scene displayed.

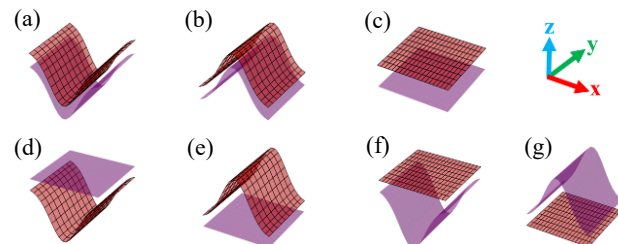


Figure 2: Actual and illusory types of the invisible surface: (a) actual valley, (b) actual ridge, (c) actual flat, (d) illusory valley, (e) illusory ridge, (f) and (g) illusory flats. [Note: The actual type matches the geometry (purple solid) of the surface with its force direction (orange mesh), whereas the illusory type mismatches the geometry with its force direction.]

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to discriminating the 3 shapes (valley, ridge, and flat) of an invisible surface. The stylus of haptic device delivered a force with its constant magnitude of 0.90 N and its direction being the derivative of the contact point between the stylus tip and the geometry of the invisible surface [2]. That is, the force direction altered according to the geometry of the surface.

The participant was not aware that each shape of the invisible surface had actual and illusionary types. As depicted in Figs. 2(a)-2(c), the actual type had a match between the geometry (purple solid) of the surface and the force direction (orange mesh). In contrast, the illusionary type was a mismatch between the geometry and force direction, as shown in Figs. 2(d)-2(g). The types were used to assess the participant's discrimination of a shape/action (valley/scooping water, ridge/dropping water, or flat/none) under the changes of force direction (a minimal sensory cue).

Each trial has three phases. The participant at first flied the helicopter while discriminating a shape/action haptically; then indicated the helicopter's action as "Scooped Water," "Dropped Water," or "None" after this flight; and finally received a recommendation (a contextual cue) of the helicopter's action from the VE algorithms. The participant could accept or reject this recommendation. Such recommendations – either reliable to align with the delivered force direction or unreliable (errors) to diverge from the force direction – were used to examine the effect of contextual cues (algorithmic errors) on haptic shape discrimination.

The surface and recommendation types yielded 4 testing sessions of trials: actual-reliable, actual-unreliable, illusionary-reliable, and illusionary-unreliable. Each reliable session had 12 trials; and each unreliable session had 24 trials (= 12 reliable + 12 unreliable). The order of the trials was pseudo-randomized, and the order of the sessions was counterbalanced among all participants. Each of the participants underwent a learning session to achieve at least 67% accuracy of shape discrimination before being involved in the 4 testing sessions and spent about 2.0 hours in the study, including breaks to minimize fatigue.

Data Acquisition and Analyses: Data were collected to compute subjective and objective metrics. One subjective metric was mental workload (*SW*) scored on a NASA-TLX questionnaire after each session. Two objective metrics were discrimination accuracy (*DA*) and judgement accuracy (*JA*) derived from VE-logged data. *DA* gauged the accuracy of discriminating the helicopter's actions, assessing the effect of the surface types. *JA* measured the accuracy of judging the recommendations, examining the effect of the contextual cues. ANOVA was used to analyze each metric, with the Jarque-Bera test for its normality and *t*-tests for comparisons.

3 RESULTS AND DISCUSSION

Collected data from all participants were analyzed for the 3 metrics. The normality test validated the adequacy of the data for a two-way ANOVA (Surface × Recommendation) on the metrics to evaluate main effects and interactions for (actual and illusionary) shapes and (reliable and unreliable) recommendations.

The results of the ANOVA for *SW* revealed no significance in Surface [$F(1,11) = 0.34, p > 0.05$], Recommendation [$F(1,11) = 1.41, p > 0.05$], and their interaction [$F(1,11) = 0.02, p > 0.05$]. This suggested that neither Surface nor Recommendation affected *SW* of the participants. As shown in Table 1, there was a significant effect of Surface on *DA* and *JA*, indicating that the participants performed better with the actual type than illusionary one. Recommendation had no effect on *DA* or *JA*, since the recommendations were offered after discriminating the helicopter's action. There was no interaction between Surface and Recommendation either.

Due to the significant influence of the surface type, *t*-tests of *DA* and *JA* compared between the actual and illusionary types of each shape/action. Both *DA* and *JA* did not differ significantly ($p > 0.05$) between the actual and illusionary types of valley/scooping water –

Table 1: Outcomes of two-way ANOVA for objectives metrics

Factors	Conditions	Mean ± SD (%)	<i>F</i> (1, 11)
Surface	Actual	<i>DA</i> : 80.74 ± 15.71 <i>JA</i> : 83.17 ± 15.21	<i>DA</i>: 2.78**
	Illusionary	<i>DA</i> : 68.58 ± 22.35 <i>JA</i> : 73.61 ± 20.03	<i>JA</i>: 8.56*
Recommendation	Reliable	<i>DA</i> : 72.58 ± 22.18 <i>JA</i> : 76.75 ± 19.65	<i>DA</i> : 1.82
	Unreliable	<i>DA</i> : 76.74 ± 17.97 <i>JA</i> : 80.03 ± 16.98	<i>JA</i> : 0.69
Interaction: Surface × Recommendation	Actual-R	<i>DA</i> : 81.97 ± 15.80 <i>JA</i> : 82.67 ± 14.81	<i>DA</i> : 4.75 <i>JA</i> : 0.71
	Actual-UR	<i>DA</i> : 79.51 ± 16.23 <i>JA</i> : 83.68 ± 16.23	
	Illusionary-R	<i>DA</i> : 63.19 ± 24.22 <i>JA</i> : 70.83 ± 22.61	
	Illusionary-UR	<i>DA</i> : 73.96 ± 19.87 <i>JA</i> : 76.39 ± 17.62	

[Note: SD for standard deviation; R: reliable; UR: unreliable; and ** and * with bolded numbers for significant differences with $p < 0.01$ and $p < 0.05$, respectively.]

as depicted in Figs. 2(a) and 2(d) – or ridge/dropping water – as shown in Figs. 2(b) and 2(e). However, the flat/none yielded significantly higher *DA* ($p < 0.01$) and *JA* ($p < 0.05$) in the actual type as shown in Fig. 2(c) than in its illusionary counterpart as depicted in Figs. 2(f) and 2(g).

Effectively, applying the force direction of an uneven shape (e.g., a valley or a ridge) onto the geometry of a flat shape enabled haptic shape discrimination under a minimal cue (i.e., the changes of the force direction), even with contextual cues in the VE. However, mapping the force direction of the flat shape onto an uneven shape did not yield the same findings, indicating a careful consideration would be needed in VE design. After all, applying the force direction of uneven shapes onto flat ones could be a straightforward approach to simplify the VE design. Due to the configuration of the hand/arm joints, these findings implied human sensitivity to various combinations of force direction and geometry. This sensitivity emphasizes the necessity of well-considered usages of sensory cues for realistic haptic rendering. Interestingly, the surface type affecting *JA* implies an intrusion of sensory cues into contextual cues, requiring future investigations.

Targeting haptic discrimination of the valley, ridge, and flat shapes – the basic components of irregular shapes, this study suggested a potential of extending its outcomes to other shapes and confirmed human ability of discriminating shapes by force cues [2, 5]. Future work should explore more shapes with more participants.

4 CONCLUSION

The study confirmed the use of a minimal cue – the changes of force direction – for shape discrimination with contextual cues in VE.

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