The Role of Multisensory Feedback in Haptic Surface Perception

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Abstract

In performing most everyday tasks, we use information from several different sensory modalities, yet our understanding of how these inputs are integrated is limited. The present study investigated the role of multisensory feedback in the perception of surface roughness, specifically focusing on whether the threshold for distinguishing the roughness of two virtual surfaces was different under visual + haptic conditions, as compared to visual-only or haptic-only conditions. Haptic stimuli were presented via the PHANToM; visual stimuli were presented via computer monitor. The virtual surfaces were sinusoidal gratings that varied in spatial period across trials. Overall, results suggested that threshold was determined by haptic input at low surface amplitudes, and by visual input at high surface amplitudes. At intermediate amplitude values, it appeared that observers were combining information across modalities to produce a percept in the combined condition that was better than that obtained under either single modality condition.

1. Introduction

While many everyday tasks can be performed using touch alone, it is more common for multiple sensory modalities (i.e., vision, hearing, etc.) to be used. However, relatively little research has investigated the specific contribution of each modality to task performance. The present study explored the impact of multisensory feedback on the perception of surface roughness. The specific question addressed is whether appropriate visual feedback, when presented together with haptic feedback, can alter the perception of virtual surface texture. As observed in earlier sensory studies with real surfaces, multimodal conditions (touch + vision) can produce very different percepts from those produced with input from one sensory modality (touch-only). It is anticipated that a similar result will occur with virtual sensing.

Previous research has given us a fair understanding of the physiology and psychophysical mechanisms underlying the texture perception of human observers when a surface is contacted by touch. The textural roughness of a surface can be sensed directly, via the bare finger, or indirectly, via a hand-held probe. Microtexture studies conducted by LaMotte & Srinivasan [8] demonstrated that humans are capable of detecting extremely fine textures. These studies explored the tactile perception of the microtexture, shape and softness of objects. The study showed that humans could actively detect fine textures composed of 50 nanometers high parallel bars etched onto a small plate of glass [8].

Bare finger vs. probe sensing

Bare finger sensing appears to have a different code for roughness perception than probe sensing. Spatial and intensive cues that derive from skin-deformation are essential to roughness perception at the fingertip. On the other hand, probe sensing relies on kinesthetic spatiotemporal cues produced by the movement of the hand and arm, and vibratory cues transmitted to the fingers through the probe. Klatzky and Lederman [6] suggest that texture perception could be done effectively with either cue. In both cases the psychophysical function of perceived roughness has an inverted U-shape [6], with perceived roughness first increasing, and then decreasing, as the spatial separation of elements on the surface is reduced. For probe sensing the point where roughness peaks and begins to decrease appears to be closely related to the diameter of the probe tip. In fact, Klatzky and Lederman [6] found that the peak was near the point where the interelement spacing exceeded the diameter of the probe.

With an increasing focus on producing and exploring simulated textures with haptic interfaces, whether telerobotic or virtual environment systems, examining the effects of the use of tools (such as probes) is becoming more important. The point-source feedback provided to the users by the haptic interfaces is similar to the information provided via probes on real surfaces. For this reason, results from probe

Proceedings of the11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS'03)
0-7695-1890-7/03 $17.00 © 2003 **IEEE**

studies are relevant for rendering realistic surfaces and objects to be experienced in virtual environments. Klatzky et al. [7] reported the results of several experiments on perceived surface roughness sensed via a rigid probe. The effects of probe speed on roughness perception were examined, as well as the existence of a roughness-constancy effect on roughness perception when surface textures were examined with a bare finger or rigid probe. Based on previous findings that the influence of surface exploration speed has little effect on perceived roughness in active and passive exploration with the bare finger [9], Klatzky et al.'s [7] study focused on probe sensing. Klatzky and colleagues believed the earlier findings could be due to a roughness-constancy effect that occurs when subjects actively explore a surface, meaning that the kinesthetic cues from active exploration cancel out any changes that are a result of the variations in speed. Results from Klatzky et al. [7] indicated that as the range of speed is reduced, roughness-constancy declines. In other words, the speed of motion affects the perceived roughness less as the range of speeds widens.

West and Cutkosky [20] made a more direct comparison of real and virtual surface textures via haptic interfaces by comparing resolution for stimuli varying in spatial frequencies as sensed by stylus or a bare fingertip. Subjects counted the number of cycles in real and virtual gratings using a stylus end-effector and compared those results to the number of cycles obtained in real gratings through bare finger sensing. Upon comparison, they found similar results for the two types of surfaces, which they interpreted as support for the validity of using haptic interfaces in human psychophysical studies. Further, they found that counting was more accurate with the fingertip for low spatial-frequency gratings and more accurate with the stylus for the higher frequencies. Since this was a counting task, it may not be possible to generalize this to texture sensing.

Texture perception involves complex interactions between the surface and end-effector exploration; therefore, the probe size should also be taken into consideration. Under some conditions, the haptic feedback via the end-effector actually yields better resolution than that obtained by the bare fingers. Although the spatial cues that would be present in bare finger exploration are absent, the kinesthetic and vibration cues available via the probe enhance the capabilities of perception.

Multimodal sensory interactions

Research investigating how one sensory modality influences the perceptual response of another sensory modality in virtual sensing is limited, especially when looking at the effects of multiple modalities; however, a few studies have addressed this topic. Hendrix et al. [5] explored the influence of multimodal virtual environment display parameters on the perception of haptic, visual, and aural material properties. While presenting subjects with a test material (real or virtual), Hendrix et al. [5] asked subjects to report on their visual, haptic, and aural observations, by matching their observations to a reference material and rating the quality of the match. Results of the experiments suggested that haptic characteristics played an important role in the matching process, while visual and aural characteristics played an important role in the quality rating of the process [5].

The question of whether multimodal presentation of stimuli results in a performance improvement or a performance decrement has been investigated in numerous studies, only a few of which are discussed here. It is possible that the addition of a second modality could divide attentional resources and thus reduce levels of performance, or that the second modality somehow interferes with the processing of the stimulus from the first modality. It is alternatively possible that the addition of the second modality provides information, some redundant and some non-redundant, that can be used by the observer to result in improvements in performance.

Some studies suggest that multimodal presentation produces a competitive effect, i.e., that the addition of a second modality can dominate the initial modality. Research by Wu et al. [21] explored the effect that 3D visual images had on the visual and haptic perception of size and stiffness in virtual environments. In the size experiments, Wu et al. [21] found that when only visual cues were provided, farther objects were perceived as smaller; however, this visual bias was altered with the addition of haptic feedback. Likewise, in the stiffness experiments when only haptic feedback was presented, farther objects appeared to be softer; however, this haptic bias was altered with the addition of visual feedback. Overall, Wu et al. [21] argued that when the sensory inputs from the visual and haptic systems are fused, perception is altered in a systematic and competitive way.

Experiments with real environments have shown that visual information can alter haptic perception of spatial properties like size, range, location, and shape [4]. Findings by Wu et al. [21] suggested that for spatial information there is a visual dominance over kinesthetic, resulting in what Srinivasan et al. [18] describe as a multimodal illusion. In other words, people tend to ignore the kinesthetic feedback and base judgments on visual feedback. In the study by Srinivasan et al. [18] subjects were asked to compare the stiffness of two virtual springs using the visual and haptic information available to them, which varied from trial to trial. In some cases the visual presentation reflected the exact opposite of the haptic presentation, which caused an increasing mismatch between visual and haptic position information leading to increasing misperception of stiffness [18]. Srinivasan et al. [18] found that stiffness can be easily identified when using one modality (e.g., vision). In a study investigating the role of auditory feedback on perceived stiffness [1], it was found that sharper impact sounds caused many subjects to overestimate the stiffness of the object they were tapping, but this was not a strong illusion for all subjects. These results suggest that the cues provided by the second modality seem to compete in some manner to modify the percept produced by a single modality.

Several studies by Lederman and colleagues have investigated the relative dominance, or compensation, of different modalities in sensing the roughness of real surfaces. Lederman et al. [12] note that, for spatial tasks, the visual system has been shown to be dominant over other modalities. However, when judgments of temporal events are of interest, the dominant system is the auditory. In Lederman et al.'s [12] study, the contributions of touch and audition to the perception of surface texture were explored. This study was most focused on the textural properties that could be discerned by the sounds produced as a person manually explores a surface. Participants made roughness judgments of a surface using a rigid probe in three conditions: touch-only, audition-only, and touch + audition. Lederman conducted a similar study in 1979 that explored the effect of touch-based auditory cues produced by the bare fingers, rather than a probe. Lederman's bare finger findings in 1979 indicated that the sense of touch dominated audition completely [10]. In contrast, Lederman et al's more recent findings [12] indicate that participants use both tactual and auditory information to make their judgments when exploring the surfaces with a rigid probe. In this case, touch cues contributed 62% and auditory cues 38% to the bimodal judgments, a considerably different result from the 100% touch dominance found in the 1979 study. This difference is largely due to the use of the rigid probe as opposed to the bare fingers for auditory exploration of surface texture. Since the sounds generated by bare fingers on a rigid surface are considerably less loud than those created by a rigid probe on a rigid surface, those softer sounds may be ignored completely [12]. Similar results, suggesting that multimodal texture judgments are a fusion of perception by the two modalities, were reported by Lederman and Abbott [11], as well as by Jones and O'Neil [2], for visual-tactile judgments of texture.

Other findings suggest that combined visual and haptic information can *improve* human perception of object properties ([3]; [15]). In the study conducted by Heller [3], subjects were asked to judge smoothness using just touch and then by using a combination of vision and touch. The results of Heller's experiment showed that touch-only was better than vision-only, particularly for very smooth surfaces. More importantly, bimodal perception led to better performance on the smoothness tasks than either single modality. In keeping with this argument, Manyam [15] found that judgments of shape were better when both vision and touch were involved, rather than touch alone.

In summary, the data suggest several possible conclusions regarding the role of multisensory feedback in haptic surface perception. Some studies (e.g., [18]) suggest that in bimodal presentation the two modalities actually compete, altering performance. Other studies (e.g., [21]; [10]) support the notion that the observer simply attends to a dominant modality and ignores the less salient modality. Finally, the findings of Heller [3] and Manyam [15] suggest that observers can integrate the input from the two modalities to produce a percept that is superior to that provided by either single modality. In the present study, the ability of observers to judge the roughness of virtual surfaces sensed via a probe was investigated under haptic-only, visual-only, and haptic + visual presentation, to examine further the question of whether the multimodal interaction was facilitatory or competitive.

2. Method

2.1 Participants

A total of 4 adults with normal sensory function (2 females, 2 males), ranging in age from 21-45, participated in the experiment. All had normal or corrected to normal vision, and reported normal tactile function. Three of the subjects had no prior experience with haptic interfaces.

2.2 Apparatus and stimuli

Haptic representations of virtual surfaces were presented by way of a PHANToM 1.0 (SensAble Devices, Inc.) 3-degree-of-freedom force feedback interface. In the present experiment, the PHANToM was interfaced to a Silicon Graphics Octane computer; software control was implemented in C++, utilizing the GHOST Toolkit provided by SensAble Devices for the PHANToM. In rendering the forces necessary to simulate the surface textures haptically, a stiffness-based force model was employed, with the stiffness coefficient set to a high value to ensure a very rigid and non-pliable surface. No additional friction coefficient was programmed, such that the surfaces were essentially "frictionless."

The PHANToM can be equipped with either a stylus (cylinder approximately 10 cm in length and about 1 cm in diameter) or a thimble, into which the user inserts the right index finger. In the present experiment, the stylus end-effector was used.

Visual representations of the surfaces were presented on a computer monitor (1280x1024 pixels, 89x89 DPI resolution), using 3-dimensional rendering (perspective, shading, etc.) with a fixed frame of reference and fixed overhead standard lighting cues. The visual display was limited to a 1.5 by 7.5 inch display window on the computer monitor to ensure that the virtual surface was being judged at the same magnification in both the visual and haptic conditions.

The virtual surfaces were sinusoidal gratings that varied in spatial period. A schematic representation is shown in Figure 1 (axes in this figure are arbitrary). Five standard grating periods were tested, ranging from .01 to .1 cm; three grating amplitude levels were tested: .01 cm, .05 cm, and .1 cm. Haptic representations were presented in the horizontal plane, and scanning was in the horizontal direction relative to the user's body. Visual representations were not superimposed on the haptic, but instead required the user to look straight ahead at the visual monitor.

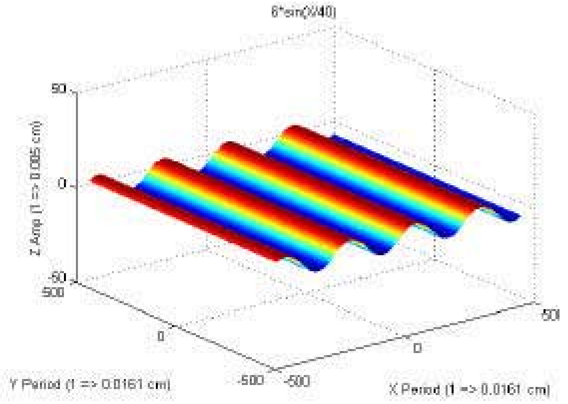

Figure 1. Schematic representation of virtual grating surface (arbitrary axes).

2.3 Procedure

On each trial, two surfaces were presented, and the observer was asked to judge which of the two surfaces was rougher in surface texture. Participants could toggle back and forth between the two surfaces using the spacebar before making the judgment as to which one was rougher. Haptic alone, visual alone, and haptic + visual presentation conditions were employed.

Across trials, the spatial period of one of the gratings (the comparison) was changed, based on the observer's response. A 2-down, 1-up adaptive procedure was used [14] to change the spatial period of the comparison surface until the two surfaces were indistinguishable. The initial step size of the change was .05 cm, and after the first reversal of response the step size was reduced to .005 cm. The program then tracked back and forth across the discrimination threshold for differentiating the two surfaces. A total of 8 reversals of response were completed for each block of trials. The average value of the spatial period of the comparison across the 8 reversals was recorded at the completion of each block.

A total of 45 conditions (5 grating periods x 3 grating amplitudes x 3 presentation conditions) were completed by each participant, with each condition taking approximately 5 to 6 minutes to complete. All participants used earplugs to eliminate auditory cues from the environment that could influence roughness judgments. Participants sat in front of the computer, to the left of the apparatus. They used the right hand to maneuver the stylus and the left hand to manipulate the keyboard to toggle between surfaces and make selections. Participants took breaks as needed throughout the experiment.

3. Results and discussion

Results were analyzed to determine whether inputs from multiple sensory modalities were integrated to produce novel percepts. In Figure 2, overall results for all 3 sensory conditions are shown as a function of grating spatial period of the standard surface, averaged across amplitudes (means and standard errors are shown). The plot displays the spatial period of the comparison surface that was just discriminable from the standard (i.e., discrimination threshold). This figure shows that overall, two-modality judgments produced slightly lower thresholds than single-modality judgments.

The data were analyzed using a three-factor (amplitude x modality x subjects), within-subjects analysis of variance (ANOVA). While the results indicated no significant main effect of stimulus amplitude, a significant main effect of modality was observed (F(2,6)=48.804, p=.0002), suggesting that the visual+haptic condition was better overall. In addition, a significant interaction (modality x amplitude) was observed (F(4,12)=8.702, p=.0016), consistent with the observation that the best performance was found for the haptic condition when the amplitude was small (.01

cm), but best performance was found for the visual condition when the amplitude was large (.1 cm).

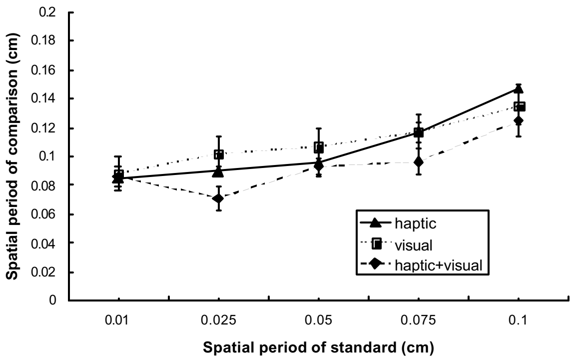

Figure 2. Grating roughness discrimination as a function of spatial period (averaged across amplitudes).

Closer inspection of the data for different surface amplitudes shows that when the amplitude is very small, haptic-only presentation yielded thresholds better than vision-only; for higher amplitudes, vision-only was better than haptic-only (see Figures 3-5). Specifically, Figure 3 shows that when the amplitudes were very small (.01 cm), the multimodal condition was highly dominated by haptic feedback. On the other hand, Figure 5 shows that for higher amplitudes the multimodal condition was highly dominated by visual feedback.

Overall, results suggested that the lowest thresholds (i.e., best resolution) were obtained in the haptic + visual conditions, as compared to either modality alone. This finding suggests that observers were combining information across modalities to produce a percept in the combined condition that was different from that obtained under either single modality condition. In cases where multimodal performance was actually better than the best single modality performance, we refer to the result as "multimodal synergy." In cases where multimodal performance was intermediate between the two single modalities, we refer to the result as "multimodal interaction." In previous studies by Lederman et al. ([13], [12]), a measure of sensory dominance was employed to determine whether touch or audition judgments had a greater impact on performance. In these studies, performance in the multimodal conditions always fell between that for the individual modalities. In the present study, the multimodal performance was often better than that in the single modality conditions. For this reason, calculating a measure of sensory "dominance" was not a useful exercise. Instead, a measure that could quantify the degree of multimodal synergy was devised.

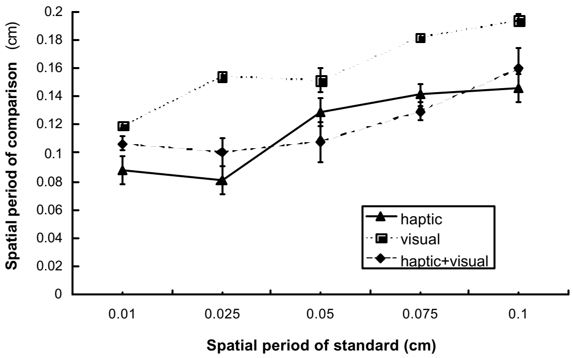

Figure 3. Grating roughness discrimination, amplitude = .01 cm.

Comparing across sensory modalities, it is possible to calculate a measure of the degree to which the combined condition differs from the single modality conditions. Using the "best" single modality condition (haptic-only or visual-only) and the multimodal condition (haptic + vision), we calculated, point-by-point, a statistic indicating the percentage of multimodal synergy present at each standard spatial period examined. In other words, synergy refers to the percent improvement in performance of the combined condition. Calculated as in (1), the percentage reflects the amount of multimodal synergy present. A positive percentage indicates the presence of a synergistic effect, while a negative percentage indicates the presence of sensory interaction.

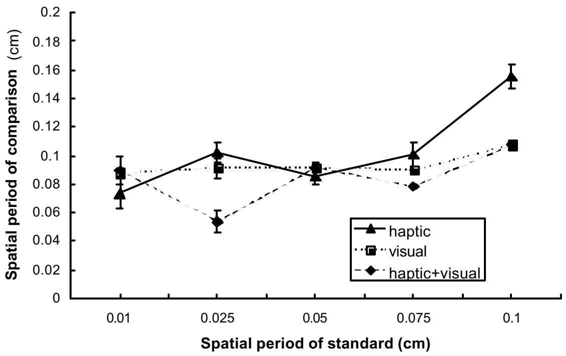

Figure 4. Grating roughness discrimination, amplitude = .05 cm.

(1) % multimodal synergy =
[(best single modality – multimodal) / (best single modality)] x 100

For the data shown in Figure 2, the overall multimodal synergy effect was approximately 9%. Due to the variance in contribution of individual modalities across amplitudes, the overall percentage of multimodal synergy does not provide a comprehensive picture of a synergistic effect. Analysis by individual amplitudes (.01, .05, .1 cm) is thus more useful (Figures 3-5). The effects of multimodal interaction, where multimodal presentation does not produce the best performance overall, can be clearly seen in Figure 3 (approx. 6%) and Figure 5 (approx. 4%). Figure 4, on the other hand, demonstrates a multimodal synergistic effect (approx. 4%).

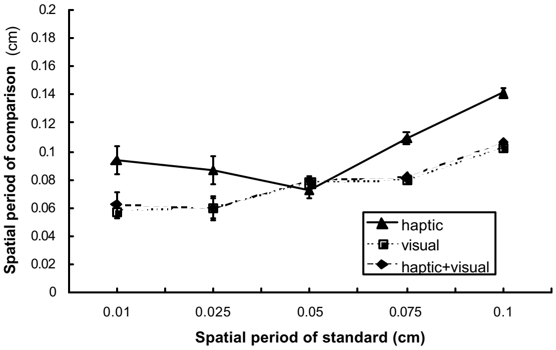

Figure 5. Grating roughness discrimination, amplitude = .1 cm.

Our findings support earlier studies by Manyam [15] and Heller [4] suggesting that bimodal feedback is better than feedback from a single modality for sensing surface properties. The results of Heller's experiment showed that touch-only was better than vision-only, particularly for very smooth surfaces. A similar trend is seen in out results. When the amplitudes were very small, the multimodal condition was highly dominated by haptic feedback; for higher amplitudes the multimodal condition was highly dominated by visual feedback. Most importantly, Heller [3] found that bimodal perception led to better performance on the smoothness tasks than just touch. In keeping with this argument, Manyam [15] found that judgments of shape were better when both vision and touch were both involved, rather than touch alone.

It is important to note that this experiment does not measure sensory function per se; rather, we are simply stating that there is a higher level of *system* performance resulting from the combined modality condition. As similarly defined by other studies with virtual sensory interfaces, here a "system" is a sensory modality working with feedback from a particular type of display. This is particularly important when viewing the results for the smallest spatial period, 0.01 cm. In this condition, the visual monitor does not provide sufficient resolution to allow the measurement of visual thresholds that reflect human visual sensitivity; however, given that the visual monitor is the typical viewing situation for many individuals in simulation settings, the fact that the addition of the haptic display permits improved performance is useful knowledge for designing improved sensory interfaces for virtual sensing.

This caveat is also important in explaining why the data do not correspond to the classic Weber's law discrimination function. Simply stated, Weber's law argues that discrimination thresholds are a function of the value of the initial standard stimulus, and that threshold should be a constant percentage of that standard. Here, the combination of human and sensory interface limitations suggests that formulations such as Weber's law are not necessarily valid in predicting discrimination ability.

This implication is demonstrated in Figure 6, which plots grating discrimination as a function of surface amplitude When visual feedback is limited (i.e., gratings were too fine to be distinguishable) at the lowest grating amplitude, haptic feedback had a greater influence in roughness discrimination. On the other hand, for higher grating amplitudes, haptic feedback has less influence (see Figure 6), and performance is largely determined by visual cues.

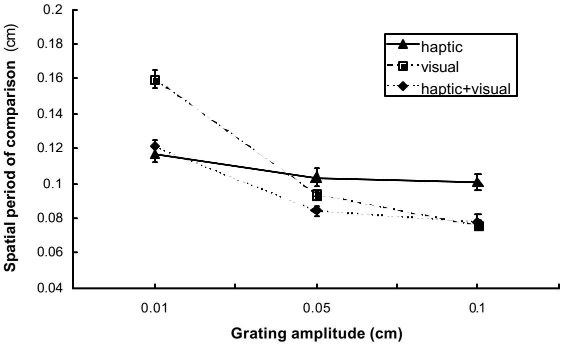

Figure 6. Grating roughness discrimination as a function of grating amplitude.

It is important to reiterate that the findings of the present study do not reflect the physical constraints of the human sensory system alone, but rather also reports the system constraints of the devices used in such studies. Specifically, it is not the visual system itself that is limited at the lower amplitudes, but the visual system combined with the computer display constraints. The pixel resolution of the screen, along with the programming constraints of the gratings, limits the observer's visual feedback. Visual performance, limited by the rather primitive visual interface used in the present study, might be considerably better with a stereo display. This issue is presently being examined in a follow-up study.

It is also not clear whether the results obtained in the present study could be used to predict performance with a wider range of grating periods or amplitudes. The values chosen for the present experiment were simply a "first pass" at the research question. In particular, these values did not address the issue of the shape of the roughness perception function. In the work by Lederman et al. described in the Introduction, these functions are typically an inverted U-shape, and the maximum point on the function is determined by the probe diameter employed.

Finally, these data bring to mind the issue of "superadditivity," which has been obtained perceptually in single modality for temporal masking for auditory [17] and vibrotactile [19] stimuli, and physiologically [16] for bimodal inputs to particular areas of sensory cortex. It is possible that the better performance at some spatial periods for bimodal presentation in the present experiment might be related to the activation of bimodally sensitive cells in sensory cortex, which respond weakly to individual visual or haptic inputs, but strongly to bimodal inputs.

As stated in the Introduction, the question of whether bimodal presentation results in perceptual competition or perceptual synergy is complex, and studies exist that support both sides of the question. Our data suggest that in certain situations combined information can improve human perception of object properties, consistent with the conclusions of Heller and Manyam ([3]; [15]). Overall, we found that multisensory input provides significant perceptual information for the discrimination of surface roughness. Furthermore, the improvements in bimodal thresholds obtained for the combined modality condition in our study have interesting implications for designers of virtual interfaces, suggesting that designers considered incorporating multimodal feedback to produce optimal performance in object sensing tasks.

4. Acknowledgments

The authors wish to thank Don Stredney and Jason Bryan of the Interface Lab at the Ohio Supercomputer Center (OSC) for their assistance with the present study. The present study was partially supported by a grant from the Dayton Area Graduate Studies Institute (HE-OSU-18-01), Ohio Board of Regents.

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