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Intra- and intermanual curvature aftereffect can be obtained via tool-touch

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Abstract—We examined the perception of virtual curved surfaces explored with a tool. We found a reliable curvature aftereffect, suggesting neural representation of the curvature in the absence of direct touch. Intermanual transfer of the aftereffect suggests that this representation is somewhat independent of the hand used to explore the surface.

Index Terms—haptic interfaces, force feedback, behavioral science, psychology

1 INTRODUCTION

HUMANS frequently explore objects in the surrounding environment via indirect touch. In this mode of exploration, an instrument or tool, rather than the hand or finger, is used to probe an object's surface (for example, when a violinist uses a bow to evoke notes from the strings of her violin). In contrast to direct touch, in which cutaneous input via mechanoreceptors signals information about local surface features at the points of contact on the object's surface [1], information obtained through indirect touch is conveyed by kinesthetic input via proprioreceptors. This kinesthetic input arises from mechanical forces of the musculoskeletal system, such as signals from the joint receptors of the elbow, Golgi tendon organs, and muscle spindles of the hand [2].

Although previous studies have shown that haptic perception in the absence of cutaneous input is diminished when discriminating some object properties, such as surface compliance [3], recent evidence suggests a greater role for kinesthetic input in forming neural representations of geometric object features, such as its shape or size, than previously believed [4], [5], [6], [7], [8], [9]. For example, Voisin and colleagues [10] asked participants to discriminate concave angles of physical surfaces by tracing surface outlines with the index finger using a dynamic mode of exploration. In the passive touch condition, the surface was passed under the finger. In the active touch condition, the finger actively explored the surface. They found that when either kinesthetic or tactile cues were removed (by immobilizing the arm to prevent kinesthetic input or by anesthetizing the finger to prevent cutaneous input) the discrimination thresholds approximately doubled, but participants could still perform the task with the degraded information.

When a physical object is explored using a bare finger, curvature perception involves integration of information about the change in the surface from a population of receptors [11]. Thus curvature may be estimated from the deformations and displacements of the fingertip's skin during movements over the surface [12], [13]. In contrast, when a tool is used rather than a bare hand, the contact with the object – made tangent to the surface at a single point – provides no immediate information about the curvature. A percept of the surface's curvature during haptic exploration with a tool requires the integration of the tangent planes over the explored region using information extracted from the remote surface. Recent studies have investigated curvature perception when observers explored a virtual curved surface using a manipulandum (a robotic arm). Henriques and Soechting [14] found reliable curvature discrimination in the active mode of exploration, in which participants were allowed to freely explore the surface using the robotic arm. Further, Squeri and colleagues found evidence for curvature discrimination in both active [8] and passive [9] exploration modes. These results suggest that although both cutaneous and kinesthetic inputs contribute to haptic perception of curvature, each input itself may make a reliable contribution.

Despite these demonstrations that kinesthetic perception of curvature is possible through both direct and indirect touch, less is known about the cortical levels of representation of curvature when a curved surface is explored indirectly with a tool-tip. Neural representations of curvature can be systematically investigated using psychophysical methods to measure adaptation aftereffects (often dubbed the psychophysicist's microelectrode [15]). Adaptation methods rely on the well-established observation that continued exposure to pre-

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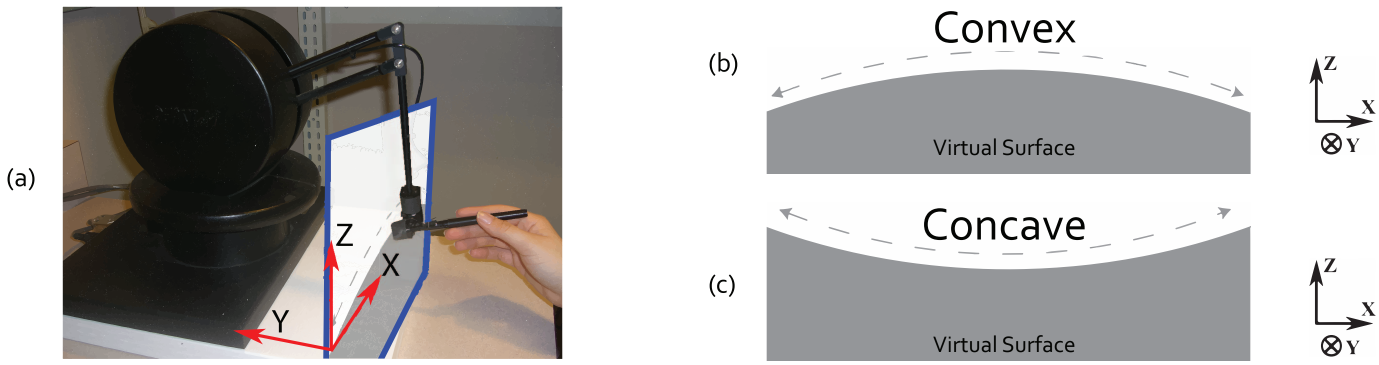

Fig. 1. Image illustrating the testing environment (a) and the concave (b) and convex virtual surfaces (c). In the testing environment (a), the endpoint of the stylus was constrained to the x-z plane (illustrated by image outlined in blue) and the participant stroked the virtual surface (illustrated by gray convex surface in x-z plane). The participants stroked the surfaces from left to right (shown as the dashed curves in b and c). Note that the height of the central point of the curvature was equivalent for concave and convex curvature.

viously explored stimuli can affect the neural representation of those stimuli. Thus, the finding of an aftereffect following exposure to a stimulus property is generally taken as evidence of the existence of specific neurons or groups of neurons that detect and process that property [16], [17].

Haptic adaptation aftereffects were first investigated by Gibson [18], who found that, after observers repeatedly touched a concave surface with their fingers, a flat test surface was perceived as convex (and vice versa: after touching a convex surface, a flat surface felt concave). This phenomenon was later examined by Vogels et al. [19], who found a curvature aftereffect when observers explored curved surface under whole-hand, direct-touch static conditions. Indeed, haptic aftereffects have been observed in various touch exploration modes, both static [19], [20] and dynamic [21].

Further, van der Horst and colleagues also found that the curvature aftereffect transferred between hands during both passive [20] and active [21] modes of exploration, suggesting that curvature information may also be represented at a stage in the somatosensory cortex shared by the fingers of both hands, involving several levels of neural processing. In addition, a larger aftereffect in active exploration compared to passive exploration suggests the importance of self-induced movement [21], which in turn suggests that representation depends on the exploration mode.

In the present study, we investigated whether curvature aftereffects would be observed in a novel tool-touch paradigm using a force-feedback device, where self-induced motion is necessary for interaction with a virtual surface. The presence of a curvature aftereffect in tool-touch would suggest higher-order integration of the point-wise surface information being processed as a neuronal representation. If, additionally, the aftereffect transfers between hands, it would suggest that surface information may also be present in a bilateral shared representation, which integrates curvature information along several stages of somatosensory processing.

2 General Methods

2.1 Participants

A total of eight participants took part in the study. Three were authors (S1, S2 and S5) and five were graduate students at Rutgers University who were naïve to the purpose of the study. Seven of the eight participants were right handed (via self report); S2 was left handed. Graduate student participants received monetary compensation for their participation. All eight individuals participated in both Experiments 1 and 2. Informed consent was obtained from all participants. The study was approved by the Rutgers University Institutional Review Board.

2.2 Stimuli and Materials

The stimuli were virtual curved surfaces presented using a PHANToM Force-feedback Device. Stimuli were programmed in C++ using the PHANToM API. These virtual surfaces were explored using the PHANToM's stylus. Since van der Horst, et al. [21] obtained reliable curvature aftereffects using real objects, we aimed to approximate those real-world conditions using the PHANToM. Constraining forces were applied in the y direction to confine exploration of the curved surface to the x-z plane (see Fig. 1a), in order to replicate the constraints of van der Horst et al.'s [21] real-world stimuli.

All curved surfaces were rendered with their midpoints at 10 cm from the base of the device. This meant that the height of the stylus was the same for all of

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the surfaces when it was horizontally centered[1]. Two adaptation curvatures ($\pm 3.2m^{-1}$) and ten test curvatures (range: $-1.6m^{-1}$ to $1.6m^{-1}$) were defined. Both convex (positive) and concave (negative) curvatures were used.

Participants were comfortably seated in front of a computer monitor with their arm supported by a cushioned surface. They held the PHANToM's stylus securely in their hand, as they would a pen or pencil. The grip of the probe was standardized for each participant by positioning the stylus between the index and middle finger and placing the thumb over the stylus. A large screen was placed between the participant and the device, blocking their view of their hand to prevent confounding exposure to visual information about the curvature that could be gleaned from seeing the hand move through space. Participants viewed a computer monitor that indicated the trial number and prompted them to respond within trials.

3 Experiment 1: Establishing the Intramanual Curvature Aftereffect

The goal of this experiment was to establish whether the curvature aftereffect could be produced via tool touch of virtual surfaces when the adapting and testing hand are the same – an intramanual curvature aftereffect.

3.1 Methods

3.1.1 Conditions

There were two adaptation conditions in Exp. 1: convex and concave. In the convex adaptation condition, participants explored a surface with a convex curvature ($+3.2m^{-1}$, see Fig. 1b for an example) and were then tested with a surface with a test curvature (either -1.60, -1.24, -0.89, -0.53, -0.18, 0.18, 0.53, 0.89, 1.24, or $1.60m^{-1}$). In the concave haptic adaptation, participants explored a concave curvature ($-3.2m^{-1}$, see Fig. 1c) and were then tested with a surface with a test curvature.

Each condition was split into two experimental sessions of 100 trials each (200 trials total for each condition, 20 repetitions per test curvature). Participants were given a brief break between the two sessions of each condition. The order of the adaptation conditions was counterbalanced across participants and the two conditions were tested with an interval of at least 24 hours between conditions.

1. Alternatively, the surface could have been constrained so that the surface left and right "edges" were always at the same height between trials and conditions or the average height of the stimuli could have been equated. The disadvantage of such experimental setup is that the distance from the home location of the stylus – where the stylus was held before adapting/testing – to the surface could have been used as a cue in curvature judgments. In addition, studies that used physical objects [20] set the height of the midpoint constant across all the curvature values, similar to our study.

3.1.2 Procedure

Trials began with a restoring force that re-centered the stylus above the virtual surface. There were two stimuli presented in each trial, an adaptation curvature surface and a test curvature surface. For each trial, participants first stroked the adapting surface back and forth. Each stroke started with the stylus at the center. Participants were instructed to move the stylus first to the right, then back through center to the left, and then back through center. This was repeated three times, for a total of 6 traversals of the surface. The stylus was then held above the surface for 4 seconds by the restoring force and then one of the 10 test curvatures was presented. Participants stroked the test surface back and forth once (2 traversals), after which the stylus was again re-centered above the virtual surface using the restoring force. They were then prompted to respond whether they perceived the test surface as concave (keyboard key 'c') or convex (keyboard key 'v').

Participants were given a short practice of a maximum of 10 trials before the initial session to familiarize themselves with the PHANToM environment and the experiment procedures. No data was recorded during practice trials.

3.1.3 Data Analysis

Proportions of "convex" responses were calculated for each participant and adaptation condition. Psychometric functions – that were modeled as cumulative Gaussian functions in these experiments – were fitted to the response data using MATLAB with the psignifit maximum-likelihood procedure [22], [23]. Each psychometric function was defined using two parameters, the point of subjective equality (PSE) – corresponding to the mean of the cumulative Gaussian – and the sensitivity – the slope of the fit.

A positive PSE value meant that the curvature of a surface was judged, on average, to be more convex. Thus, a positive PSE would mean that a flat surface ($curvature = 0$) was judged to be convex ($curvature > 0$). Likewise, a negative PSE would mean that the same flat surface would be judged to be concave ($curvature < 0$). The difference threshold, describing the minimum perceptible difference between curvatures, was defined as the average of the curvature difference between the 75% point on the psychometric curve and the PSE (50% point) and the PSE and the 25% point (note that since the model fits were cumulative Gaussian distributions these differences were equal). Higher difference thresholds meant that individuals were less sensitive to differences in curvatures and, likewise, lower thresholds showed higher sensitivity to differences. The difference between the PSEs for the two adaptation conditions – a measure of the magnitude of the aftereffect – was also calculated. No difference between the PSEs would mean there was no perceptual aftereffect due to the adapting surfaces.

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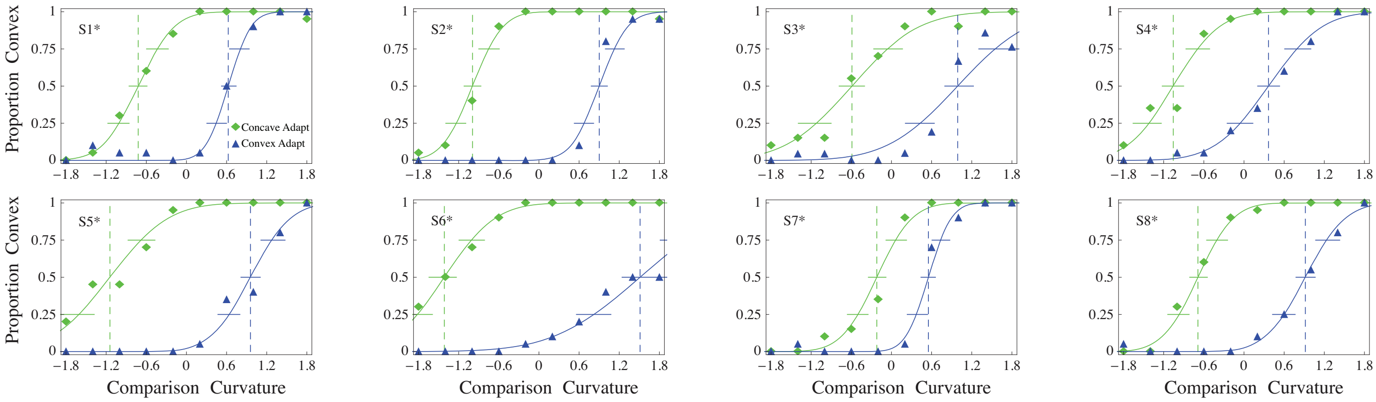

Fig. 2. Plots illustrate the psychometric functions obtained from the concave (green diamonds) and convex (blue triangles) intramanual adaptation conditions in Exp. 1 with the dashed vertical lines indicating the points of subjective equality (PSEs). The horizontal lines intersecting the psychometric curve illustrate the 95% confidence intervals of the fit for the 25%, 50% (PSE), and 75% proportion correct points on the curves. Note the significant aftereffect for every participant. Stars (*) indicate participants with significantly different PSEs ($p < 0.05$).

3.2 Results

The psychometric functions for the two adaptation conditions are shown in Fig. 2. All eight of the participants showed aftereffects in the predicted directions. After adapting to the concave surface, participants' PSEs ranged from -1.414 to $-0.219m^{-1}$ ($M = -0.853m^{-1}, SD = 0.373m^{-1}$). Concave adaptation difference thresholds ranged from 0.242 to $0.531m^{-1}$ ($M = 0.357m^{-1}, SD = 0.102m^{-1}$). After adapting to a convex surface, participants' PSEs ranged from 0.367 to $1.511m^{-1}$ ($M = 0.852m^{-1}, SD = 0.348m^{-1}$). Convex adaptation difference thresholds ranged from 0.181 to $0.687m^{-1}$ ($M = 0.362m^{-1}, SD = 0.184m^{-1}$). The aftereffect magnitude (Convex adaptation PSE - Concave adaptation PSE) ranged from 1.346 to $2.925m^{-1}$ ($M = 1.706m^{-1}, SD = 0.631m^{-1}$).

Individual ANOVAs with comparison curvature and adaptation condition as factors and the proportion convex as the dependent variable confirmed that there was a significant difference between adaptation conditions for all 8 participants (S1: $F(1,380) = 146.66, p < 0.01$; S2: $F(1,380) = 467.49, p < 0.01$; S3: $F(1,380) = 149.06, p < 0.01$; S4: $F(1,380) = 149.42, p < 0.01$; S5: $F(1,380) = 317.44, p < 0.01$; S6: $F(1,380) = 467.44, p < 0.01$; S7: $F(1,380) = 66.19, p < 0.01$; S8: $F(1,380) = 230.30, p < 0.01$).

The results of Experiment 1 showed that exploration of curved surfaces using indirect touch produced a haptic curvature aftereffect. To investigate whether the curvature aftereffect was limited to the hand with which participants explored the surface, we conducted a second experiment where participants adapted to a curved surface with one hand and tested with the other.

4 Experiment 2: Intermanual Transfer

In the previous experiment, we demonstrated that adapting to a curved surface would lead to a curvature aftereffect using virtual surfaces. This experiment was used to examine whether this curvature aftereffect transferred between hands.

4.1 Methods

4.1.1 Conditions

As in Exp. 1, there were two adaptation conditions: concave and convex. The adaptation and testing curvature parameters were identical to those used in Exp. 1.

4.1.2 Procedure

The procedure was similar to Exp. 1. The main difference was that participants adapted to a curved surface with one hand, then switched hands and explored the test surface with their other hand. Seven of the eight participants used their dominant hands for adaptation and non-dominant hand for test; S3 tested with non-dominant hand for adaptation and dominant hand for test due to a miscommunication about handedness. Another difference in the experimental setup was that a foam-core frame draped with a curtain was placed around the front of the device, so that participants could place their hands through the frame with the view of their hands blocked.

4.1.3 Data Analysis

Data analyses were conducted in the same manner as in Exp. 1, with psychometric curves fit to the observers' responses for each condition.

4.2 Results

Figure 3 shows the psychometric functions obtained for Exp. 2. Six of the eight participants had aftereffects in the predicted directions. After adapting to a concave surface with one hand and testing with the other hand, participants' PSEs ranged from -0.692 to $0.132m^{-1}$ ($M = -0.288m^{-1}, SD = 0.295m^{-1}$). Concave

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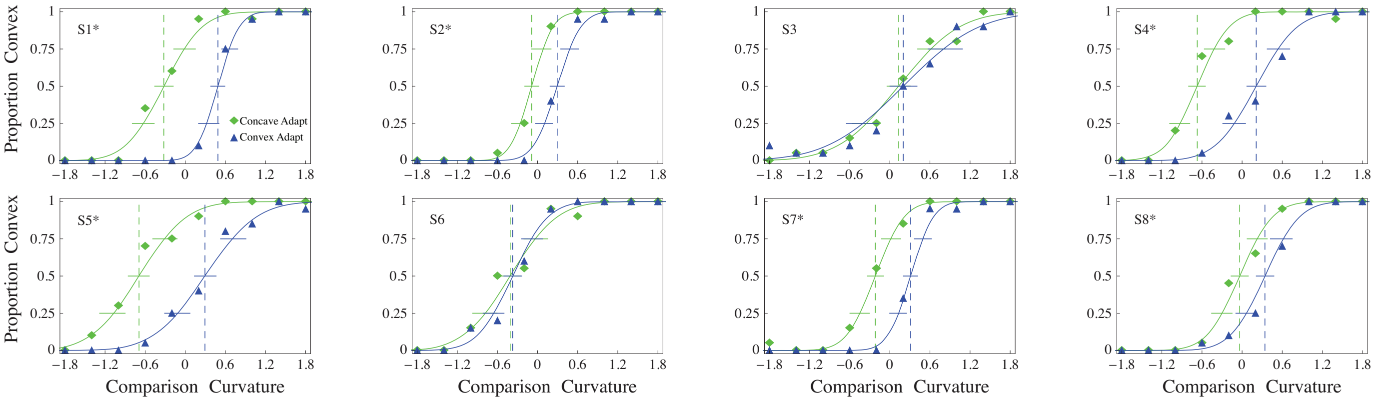

Fig. 3. Psychometric curves showing curvature aftereffects obtained in the concave (green diamonds) and convex (blue triangles) intermanual adaptation conditions in Exp. 2. The horizontal lines intersecting the psychometric curve illustrate the 95% confidence intervals of the fit for the 25%, 50% (PSE), and 75% proportion correct points on the curves. Note the intermanual aftereffects are in the same direction as the intramanual aftereffects for the majority of participants. Stars (*) indicate participants with significantly different PSEs ($p < 0.05$).

adaptation difference thresholds ranged from 0.170 to $0.482m^{-1}$ ($M = 0.307m^{-1}, SD = 0.100m^{-1}$). After adapting to a convex surface, participants' PSEs ranged from -0.372 to $0.488m^{-1}$ ($M = 0.221m^{-1}, SD = 0.256m^{-1}$). Convex adaptation difference thresholds ranged from 0.170 to $0.602m^{-1}$ ($M = 0.305m^{-1}, SD = 0.145m^{-1}$). The aftereffect magnitude for the intermanual conditions ranged from 0.037 to $0.986m^{-1}$ ($M = 0.508m^{-1}, SD = 0.360m^{-1}$).

Individual ANOVAs with comparison curvature and adaptation condition as factors and the proportion convex as the dependent variable confirmed that there was a significant difference between adaptation conditions for 6 of the 8 participants (S1: $F(1, 380) = 89.97, p < 0.01$; S2: $F(1, 380) = 23.32, p < 0.01$; S4: $F(1, 380) = 71.56, p < 0.01$; S5: $F(1, 380) = 71.39, p < 0.01$; S7: $F(1, 380) = 38.92, p < 0.01$; S8: $F(1, 380) = 17.19, p < 0.01$). Two participants did not have significant differences between the concave and convex intermanual conditions (S3: $F(1, 380) = 0.37, p > 0.05$; S6: $F(1, 380) = 0.32, p > 0.05$).[2] There was a significant difference between the two experiments, confirmed by a paired samples t-test, $t(7) = 4.07, p < 0.01$. Figure 4 illustrates the aftereffect magnitudes for Exp. 1 (intramanual adaptation) and Exp 2 (intermanual adaptation).

The results of Exp. 2 showed that exploration of a curved virtual surface with a stylus produced an adaptation curvature aftereffect, even though different hands were used for adaptation and testing.

5 General Discussion

We demonstrated that a haptic curvature aftereffect can be obtained when a virtual surface is explored using a

2. Participant S3 did not show intermanual transfer of the curvature aftereffect; however, we do not believe that this was due to testing hand order, as another participant (S6) who adapted with their dominant hand and tested with their non-dominant hand also did not show transfer.

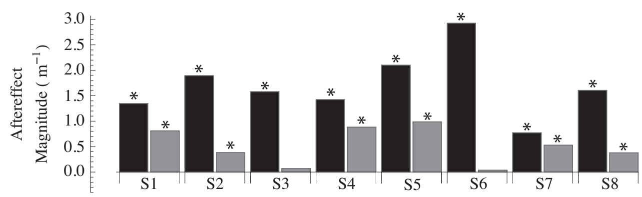

Fig. 4. Bar graph illustrating the aftereffect magnitude for both Exp. 1 (intramanual adaptation, black bars) and Exp. 2 (intermanual adaptation, gray bars). Exp. 2 had lower aftereffect magnitudes, but all aftereffects across the two experiments were significantly larger than zero except for S3 and S6's intermanual adaptation condition. Stars (*) indicate significant aftereffects ($p < 0.05$).

tool, and showed that it transfers between hands. This finding, that curvature information can be confidently acquired from the tip of a tool exploring a virtual curved surface, improves our understanding of how object properties are processed by the haptic system and extends previous findings that investigated haptic curvature aftereffect using physical objects (e.g., [18], [21]). Experiment 1 demonstrates that proprioceptors play an important role in encoding curvature information without cutaneous inputs from immediate skin contact with the surface. Further, the presence of the curvature aftereffect in the absence of direct cutaneous input suggests that populations of neurons that process proprioceptive inputs may be involved in the neural representation of surface curvature.

In Experiment 2, the haptic curvature aftereffect was also demonstrated in the intermanual active exploration condition in which participants adapted with one hand, and tested with the other hand. Participants' performance pattern is consistent with the adaptation aftereffect, suggesting that input from each hand projects to a common neural curvature representation. This finding is in line with work by van der Horst et al. [21] who found intermanual transfer of the curvature aftereffect when physical surfaces were actively explored with the finger, and suggested that higher levels of somatosensory processing may contribute in representation of curvature.

While previously van der Horst and colleagues [21] found that magnitudes of the aftereffect were similar for inter- and intramanual dynamic touch conditions, we found that the magnitude of the aftereffect in our Exp. 2 was smaller, overall, when compared to Exp. 1 (see Fig. 4), with two participants failing to show significant transfer in the intermanual condition (S3 and S6). One possibility for the weaker effect in Exp. 2 is that curvature information derived from tool-touch may be less reliable than information derived from direct touch when transferring between hands. Additionally, perceptual performance may be affected by unaccounted stiffness and temporal delays introduced by the haptic force-feedback controller. Indeed, previous work has shown that tool touch exploration can lead to elevated thresholds of the properties being explored [7].

Taken together, our findings suggest that virtual curvature explored with a tool-tip can be processed along multiple cortical levels. A question that remains open is what this curvature representation entails. One possibility is that for each of these levels there exist perceptual invariants [12] related to self-induced movement of tool-held hand and arm that provide information for haptic processing of curvature. For example, in our experiments, exploring a convex surface with a stylus has a distinct trajectory for the wrist – proximally pronate to distally neutral – that differs from exploring a concave surface – proximally neutral to distally pronate. Different surface shapes and curvatures require different hand and arm movement profiles. This kinematic interpretation of our results suggests that curvature adaptation may reflect adaptation to a particular movement pattern associated with a given curvature. Further work is needed to explore this possibility.

6 Conclusion

Information about surface curvature of objects requires integration of input from distinct points across an object's surface. This study demonstrated that such information can be obtained when a virtual surface is explored indirectly using a tool. Our results show that the inputs to the neural representation of curvature are not limited to inputs derived exclusively from direct touch. We further demonstrated that the aftereffect transfers between hands; adapting to a surface with one hand alters the perception of the curvature of a surface explored with the other hand, suggesting that the representation of the curved virtual surface is not necessarily dependent on the hand used to explore the surface.

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