Isotropy and visual modulation of haptic force direction discrimination on the human finger

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ABSTRACT

In this review, we summarize the findings from two recent studies that have investigated haptic force direction discrimination thresholds in adult humans. Haptic force vectors originating from one of five different force directions were presented to the index finger of participants. Discrimination thresholds were measured using a three-interval one-up three-down adaptive procedure. In contrast to the literature on the anisotropy of haptic perception, the results of the two experiments suggest that the acuity of the haptic perception of force direction is not directionally dependent. This review paper also examines the relative contributions of haptic and visual information to the generation of coherent multisensory percepts.

Keywords: haptic, force direction, discrimination threshold, visual, psychophysics, multisensory integration, sensory dominance

1 INTRODUCTION

Force information is an important attribute of haptic perception. For instance, as a person uses his/her fingers to explore a surface during active haptic exploration, the constant update of force feedback cues inform the person about his/her experience, such as whether he/she is moving along a smooth and sloping surface. A number of researchers have noted that the experience of force cues dominates haptic sensation in the sense that when conflicting geometrical and force information are presented, participants will typically perceive the shape of an object in a manner that is consistent with the information provided by the force cues rather than with that provided by the geometric cues [23]. A recent study on curvature perception has demonstrated that participants give a higher weight to force cues than position cues when the arches are shallow, and a higher weight to position cues than force cues when the arches are convex. Such results therefore generalize the force-dominance view of [23] to a model of weighted force and position cues in haptic curvature judgments [5]. Another recent study has also shown that the forces produced when participants actively explored a virtual haptic display would influence the haptic estimation of length [36].

Although much is known about the perception of force magnitude [14][21], few studies have investigated the perception of force direction (though see [17]) presumably due to the lack of experimental apparatus capable of delivering 3-D force vectors in a controlled manner. The advent of force-feedback haptic devices now makes it possible to measure, for example, people’s sensitivity to changes in force direction. This is an important metric for designers of haptic virtual environments since the perception of virtual objects by humans depends on both the magnitude and the direction of reactive forces. The authors have recently conducted two experiments to assess the ability of human participants to perceive force direction [1], [31]. Specifically, we investigated whether force direction discrimination thresholds are isotropic [31] and whether the visual representation of vector directions has any influence on the haptic discrimination of force directions [1].

2 HAPTIC PERCEPTION OF FORCE DIRECTION

In one recent study, Tan et al. [31] used a three-interval one-up three-down adaptive procedure [19] to measure the discrimination thresholds of haptic force direction presented to the index finger of twenty-five participants using a PHANToM force-feedback device. The force directions were presented from five different force vectors, including the top (up), left, right, diagonal left, and diagonal right (see Figure 1). The participants were required to discriminate from among three sequentially-presented haptic stimuli the one that was presented from a direction that was different to the other two. Threshold values for each of the five force directions were determined (using a within-participants design) and are depicted in Figure 1.

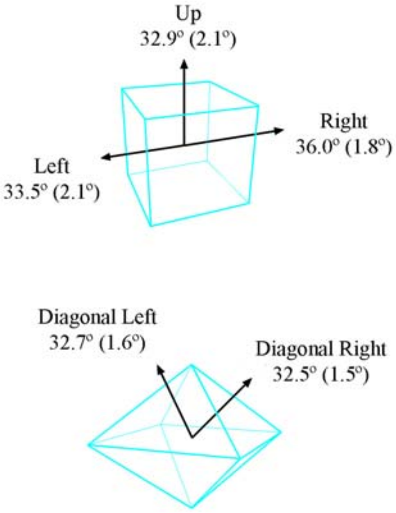

Figure 1 : The five force vectors used as the reference force directions in [31] and [1], together with the estimated mean thresholds of haptic force direction discrimination reported in [31] (and their standard errors in parentheses).

In contrast to the extensive literature on the anisotropy of haptic perception (e.g., [8][11]), the results of Tan et al.’s [31] experiment suggested that the perception of force direction

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was not directionally dependent (cf. [8]). This means that the acuity of haptic force direction perception is more-or-less the same regardless of the direction from which the force is applied. While it may have been the case that the isotropy of haptic force direction discrimination thresholds resulted from a failure to properly align the relative positions of the PHANToM device (hence its cardinal directions) to the human torso, it should be noted that achieving such alignment would represent a challenging task. Nevertheless, the haptic force direction thresholds (see Figure 1) should prove particularly useful for the design of haptic devices and for fine-tuned rendering algorithms. For example, the relatively large discrimination thresholds (>30°) provide an upper bound for the amount of distortion that can be introduced by force-smoothing algorithms in order to achieve better stability and smoother object surfaces without introducing discernable artifacts. Note though that the generalization of these findings may be limited to force direction perception on the fingertip and/or the specific force magnitude profile tested. Note also that it is debatable whether the spatial reference frame for haptic perception is centered on certain body parts (such as the head or hand, i.e., involving an egocentric frame of reference) or rather on an allocentric frame of reference (i.e., defined by environmental cues, cf. [20]). It would therefore be interesting in future research to examine the discrimination thresholds for forces applied to other body parts, such as, for example, the palm, wrist, forearm, etc. (see [32]; cf. [11]).

Toffin et al. [32] examined the capacity of adult human participants to reproduce forces applied to their hand by instructing the participants to either passively perceive a reference force on a joystick and adjust a subsequently-presented force to the same direction as the reference force, or to actively remember the reference force and reproduce a force that was sufficient to resist the reference force. Toffin et al. examined 24 reference force directions in the horizontal plane and found no anisotropy in the perception of force direction, just as in Tan et al.'s [31] study. Toffin et al. concluded that humans encode the efforts required to reproduce a perceived force rather than encoding the perceived force vector information. Toffin et al.'s findings hint at the rather poor sensitivity of haptic force discrimination, again consistent with an overall mean threshold of 33° reported in Tan et al.'s study. It should, however, also be noted that the ability to reproduce a force direction or movement may be distorted at the stage of motor response, and that this should be distinguished from the ability to perceive a given force direction.

3 VISUAL-HAPTIC MULTISENSORY INTEGRATION

The multisensory integration approach to human information processing (see [3]) suggests that people integrate the sensory information available to their various different sensory modalities (e.g., vision, audition, touch, olfaction, and taste) in order to generate a coherent multisensory perceptual experience of the external world. Given the poor haptic resolution of force direction, and given that the maximum-likelihood estimation (MLE) theory suggests that the most accurate modality normally dominates over the other sensory inputs [6][7], one might predict a larger influence of vision over haptics in force direction discrimination when some form of conflict is introduced. However, it is important to note that the MLE model is typically only applicable for small conflicts (i.e., of up to approximately 11% difference between the constituent signals). Beyond this point, people may start to treat the sensory stimuli as representing separate and independent events (cf. [24]). The investigation of the integration of visual-haptic information is important both for real-world interactions and for interactions taking place in virtual environments. Previous studies have examined the various parameters for such visual-haptic integration. Back in the 1960s, Rock and colleagues [24][25] investigated the extent to which vision dominates the sense of touch and biases the haptic perception of size and shape (see also [12]). Since then, many other researchers have also examined situations of multisensory conflict (e.g., see [4][15][16][17][18][22][26][27][33][34][35]).

In another recent experiment, Barbagli et al. [1] examined the influence of visual information on the perception of haptic force direction, with the visual information being either congruent or incongruent with the haptic forces that were presented (see [1]). In this study, the participants made force direction discrimination responses similar to those described above in Tan et al.'s [31] study, with the exception that in one condition, congruent visual information that indicated the valid direction of the haptic force was presented, while in another condition, incongruent visual information was presented (see Figure 2), or else no visual information was presented (the haptic only condition). The participants were told prior to the start of the experiment that the visual information might sometimes be misleading, and that they should therefore respond according to the haptic sensation felt. Three separate threads of adaptive staircases were run for each of the three conditions, with trials from the three conditions presented randomly intermixed in the same experimental block of trials (see Figure 3). Twenty participants were individually tested on one of the five force vectors (i.e., 4 participants were tested in each direction). Consistent with the notion that haptic perception is influenced by visual information (cf. [17]), a significant effect of congruency was found with congruent visual information lowering the haptic force direction discrimination threshold to 18.4° (SE = 2.4°) from the threshold of 25.6° (SE = 1.7°) seen in the haptic only condition, while the incongruent visual information led to an increase in the threshold to 31.9° (SE = 2.6°). The results also failed to reveal any statistically significant difference across the five force directions tested, thus confirming Tan et al.'s [31] earlier findings.

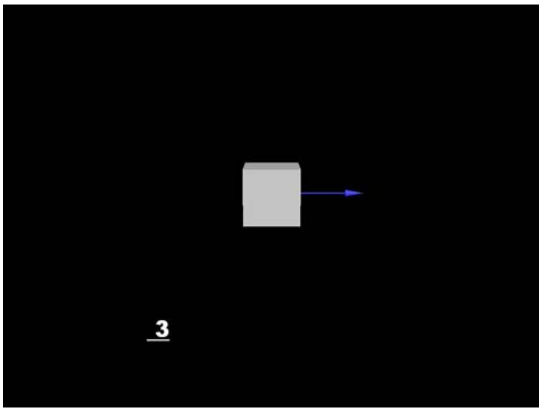

Figure 2 : A screenshot of the visual information that participants in [1] saw on the computer monitor. The arrow (blue) changed in synchrony with the haptic force magnitude: Specifically, it moved rapidly out from the center of the white cube until it reached the predetermined maximum length (3.5 cm) and then shrank back to the center.

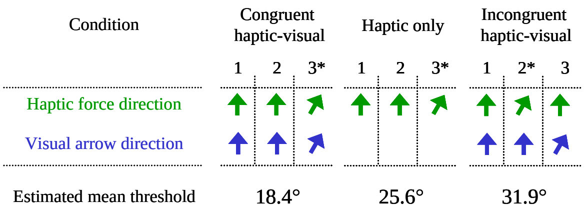

Figure 3 : An illustration of a sample trial in each of the three conditions in [1]. In this example, the target force direction occurred in the interval indicated by *. The estimated mean thresholds for each conditionas reported in [1] are also shown.

Presumably the haptic force discrimination thresholds obtained from Barbagli et al.'s [1] study in the presence of congruent visual information may be closer to those of a visual only condition (an overall mean of 3.3°) reported in a follow-up experiment. However, given that the visual information was valid (i.e., reliable and useful for the haptic task) on only 2/3 of the trials where visual cues were present, and that the haptic only condition was interleaved in the experimental run, the participants might have concentrated on the haptic task (as, in fact, they were instructed to) while weighing the visual information as relatively less important (or at least attempting to ignore it).

Battaglia et al. [2] suggested that endogenous attention may have a residual effect on the optimal integration of multisensory information. In particular, Battaglia and colleagues pointed out that the MLE model may fail to account for any perceptual biases that observers might have. They found that the MLE model consistently underestimated the extent to which participants in an audio-visual spatial localization experiment biased their responses to vision. This means that the role of visual capture in general may not have been accounted for satisfactorily by the MLE model.

It seems intuitive that haptic information would provide the most accurate sensory cues with regard to the discrimination of force direction. As a result, haptics should dominate when it is in conflict with vision. However, our results suggest that vision can modulate haptic perception. Our results would therefore suggest the need for some reconsideration of how to determine what constitutes the 'most accurate' modality in this context.

One may argue that the visual estimates available to the participants were artificially assigned by the experimenter (i.e., the participants did not see the force being applied to the finger per se, but rather a visual representation of the force direction, and the participants had prior knowledge that the visual cue might not correspond to the haptic force direction felt). Thus, it could be argued that the visual cues were more salient than those normally available when making force direction judgments in a real-world situation. It is also possible that these findings reflect sensory interference, or some kind of Garner interference effect (i.e., crossmodal interference taking place at a more decisional, rather than perceptual, level of information processing; see [9][30]).

In Barbagli et al.'s [1] study, the haptic and visual information were presented from two distinct spatial locations (an experimental set-up which is common to the majority of visual-haptic studies). The setting resembled that of the familiar manipulation of a computer mouse placed on the side of a person and used to control the mouse pointer displayed on a computer monitor (placed directly in front of a person; see [13]). Given recent evidence that spatial proximity can influence the integration of visual and haptic cues (see [10][28]), the effects of visual cues on haptic force perception might be expected to be more pronounced when the visual cues are presented from the same spatial location as the haptic stimuli, as opposed to from different positions, such as in the study described here.

4 CONCLUSIONS

In conclusion, our findings suggest that (1) haptic force direction discrimination is not directionally dependent (i.e., it appears to be isotropic); and that (2) the recommended force direction discrimination threshold for use in the design of haptic devices is on the order of 25-33°. Note that these thresholds are, if anything, likely to be elevated under conditions where people have to attend to other locations (or to divide their attention between different sensory modalities), as compared to the best-case scenario tested in the experiments outlined here, where the participants were explicitly instructed to direct their full attention to the discrimination of force directions applied to their index finger (cf. [29]). Accordingly, system designers may be able to take advantage of an even larger tolerance than the threshold values suggested here, given that attention will not necessarily be concentrated on the manipulation of the haptic tool alone. With respect to the integration of visual-haptic information, designers of haptic virtual environments nevertheless need to pay close attention to the parameters of signal reliability [6], attentional bias [2][29], and spatial proximity [10] of the visual and haptic information sources.

REFERENCES

[1] F. Barbagli, K. Salisbury, C. Ho, C. Spence, and H. Z. Tan. Haptic discrimination of force direction and the influence of visual information. *ACM Transactions on Applied Perception*, in press.

[2] P. W. Battaglia, R. A. Jacobs, and R. N. Aslin. Bayesian integration of visual and auditory signals for spatial localization. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision*, 20(7): 1391-1397, 2003.

[3] G. A. Calvert, C. Spence, and B. E. Stein (Eds.). *The handbook of multisensory processes*. Cambridge, MA: MIT Press, 2004.

[4] G. L. Diewert and G. E. Stelmach. Intramodal and intermodal transfer of movement information. *Acta Psychologica*, 41(2-3): 119-128, 1977.

[5] K. Drewing and M. O. Ernst. Integration of force and position cues for shape perception through active touch. *Brain Research*, 1078(1): 92-100, 2006.

[6] M. O. Ernst and M. S. Banks. Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870): 429-433, 2002.

[7] M. O. Ernst and H. H. Bulthoff. Merging the senses into a robust percept. *Trends in Cognitive Sciences*, 8(4): 162-169, 2004.

[8] E. A. Essock, W. K. Krebs, and J. R. Prather. Superior sensitivity for tactile stimuli oriented proximally-distally on the finger: Implications for mixed class 1 and class 2 anisotropies. *Journal of Experimental Psychology: Human Perception & Performance*, 23(2): 515-527, 1997.

[9] W. R. Garner. The stimulus in information processing. *American Psychologist*, 25: 350-358, 1970.

[10] S. Gepshtein, J. Burge, M. O. Ernst, and M. S. Banks. The combination of vision and touch depends on spatial proximity. *Journal of Vision*, 5(11): 1013-1023, 2005.

[11] G. O. Gibson and J. C. Craig. Tactile spatial sensitivity and anisotropy. *Perception & Psychophysics*, 67(6): 1061-1079, 2005.

[12] J. J. Gibson. Adaptation, after-effect and contrast in the perception of curved lines. *Journal of Experimental Psychology*, 16: 1-31, 1933.

[13] N. P. Holmes and C. Spence. Beyond the body schema: Visual, prosthetic, and technological contributions to bodily perception and awareness. In G. Knoblick, I. M. Thornton, M. Grosjean, and M. Shiffrar (Eds.), *The human body: From the inside out*, pp. 15-64, Oxford: Oxford University Press, 2006.

[14] L. A. Jones. Matching forces: Constant errors and differential thresholds. *Perception*, 18(5): 681-687, 1989.

[15] J. A. S. Kinney and S. M. Luria. Conflicting visual and tactual-kinesthetic stimulation. *Perception & Psychophysics*, 8(3): 189-192, 1970.

[16] R. L. Klatzky, S. Lederman, and C. Reed. There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology: General*, 116(4): 356-369, 1987.

[17] R. M. Klein. Attention and visual dominance: A chronometric analysis. *Journal of Experimental Psychology: Human Perception and Performance*, 3(3): 365-378, 1977.

[18] S. J. Lederman, G. Thorne, and B. Jones. Perception of texture by vision and touch: Multidimensionality and intersensory integration. *Journal of Experimental Psychology: Human Perception & Performance*, 12(2): 169-180, 1986.

[19] H. Levitt. Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America*, 49(2): 467-477, 1971.

[20] M. Luyat, E. Gentaz, T. R. Corte, and M. Guerraz. Reference frames and haptic perception of orientation: Body and head tilt effects on the oblique effect. *Perception & Psychophysics*, 63(3): 541-554, 2001.

[21] X. D. Pang, H. Z. Tan, and N. I. Durlach. Manual discrimination of force using active finger motion. *Perception & Psychophysics*, 49(6): 531-540, 1991.

[22] H. L. Pick, Jr., D. H. Warren, and J. C. Hay. Sensory conflict in judgments of spatial direction. *Perception & Psychophysics*, 6(4): 203-205, 1969.

[23] G. Robles-De-La-Torre and V. Hayward. Force can overcome object geometry in the perception of shape through active touch. *Nature*, 412(6845): 445-448, 2001.

[24] I. Rock and C. S. Harris. Vision and touch. *Scientific American*, 216(5): 96-104, 1967.

[25] I. Rock and J. Victor. Vision and touch: An experimentally created conflict between the two senses. *Science*, 143: 594-596, 1964.

[26] T. Seizova-Cajic. Size perception by vision and kinesthesia. *Perception & Psychophysics*, 60(4): 705-718, 1998.

[27] H. J. Snijders, N. P. Holmes, and C. Spence. Direction-dependent integration of vision and proprioception in reaching under the influence of the mirror illusion. *Neuropsychologia*, in press.

[28] S. Soto-Faraco, J. Lyons, M. Gazzaniga, C. Spence, and A. Kingstone. The ventriloquist in motion: Illusory capture of dynamic information across sensory modalities. *Cognitive Brain Research*, 14(1): 139-146, 2002.

[29] C. Spence, M. E. R. Nicholls, and J. Driver. The cost of expecting events in the wrong sensory modality. *Perception & Psychophysics*, 63(2): 330-336, 2001.

[30] C. Spence and M. Walton. On the inability to ignore touch when responding to vision in the crossmodal congruency task. *Acta Psychologica*, 118(1-2): 47-70, 2005.

[31] H. Z. Tan, F. Barbagli, K. Salisbury, C. Ho, and C. Spence. Force-direction discrimination is not influenced by reference force direction (short paper). *Haptics-e: The Electronic Journal of Haptics Research*, 4(1): 1-6, 3-Feb-2006. (http://www.haptics-e.org)

[32] D. Toffin, J. McIntyre, J. Droulez, A. Kemeny, and A. Berthoz. Perception and reproduction of force direction in the horizontal plane. *Journal of Neurophysiology*, 90(5): 3040-3053, 2003.

[33] R. J. van Beers, D. M. Wolpert, and P. Haggard. When feeling is more important than seeing in sensorimotor adaptation. *Current Biology*, 12(10): 834-837, 2002.

[34] S. A. Wall and W. S. Harwin. Interaction of visual and haptic information in simulated environments: Texture perception. In *Proceedings of the 1st Workshop on Haptic Human Computer Interaction*, pp. 39-44, 2000.

[35] R. B. Welch and D. H. Warren. Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, 88(3): 638-667, 1980.

[36] P. Wydoodt, E. Gentax, and A. Streri. Role of force cues in the haptic estimations of a virtual length. *Experimental Brain Research*, 171(4): 481-489, 2006.