Current Biology 20, 223–225, February 9, 2010 ©2010 Elsevier Ltd All rights reserved DOI 10.1016/j.cub.2009.11.069

Report

Poor Haptic Orientation Discrimination in Nonsighted Children May Reflect Disruption of Cross-Sensory Calibration

Monica Gori,[1,*] Giulio Sandini,[1] Cristina Martinoli,[2] and David Burr[3,4]
[1]Robotics, Brain and Cognitive Sciences, Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy
[2]Istituto David Chiossone, Corso Armellini 11, 16122 Genoa, Italy
[3]Dipartimento di Psicologia, Università Degli Studi di Firenze, Via S. Salvi 12, 50125 Florence, Italy
[4]Institute of Neuroscience, CNR Pisa, Via Moruzzi 1, 56124 Pisa, Italy

Summary

A long-standing question, going back at least 300 years to Berkeley's famous essay, is how sensory systems become calibrated with physical reality. We recently showed [1] that children younger than 8–10 years do not integrate visual and haptic information optimally, but that one or the other sense prevails: touch for size and vision for orientation discrimination. The sensory dominance may reflect cross-modal calibration of vision and touch, where the more accurate sense calibrates the other. This hypothesis leads to a clear prediction: that lack of clear vision at an early age should affect calibration of haptic orientation discrimination. We therefore measured size and orientation haptic discrimination thresholds in 17 congenitally visually impaired children (aged 5–19). Haptic orientation thresholds were greatly impaired compared with age-matched controls, whereas haptic size thresholds were at least as good, and often better. One child with a late-acquired visual impairment stood out with excellent orientation discrimination. The results provide strong support for our crossmodal calibration hypothesis.

Results

We used the child-friendly technique described in Gori et al. [1] to measure haptic discrimination thresholds for size and orientation discrimination in a group of 18 visually impaired children (5–19 years of age: 17 congenital, 1 acquired). Measurements were made with a two-interval forced-choice procedure. Two physical stimuli were presented sequentially on each trial, plastic blocks (average height 50 mm) for the size discrimination and tilted bars (average angle 45°) for the orientation discrimination; children reported which stimulus (first or second) was higher or slanted more clockwise (see Supplemental Experimental Procedures and Movie S1, available online, for details). One stimulus (randomly first or second) was the standard, always 55 mm high (for size) or 45° slant (for orientation), and the other the probe, of variable height (45–65 mm) or orientation (0°–90°). The height and the orientation of the probe were varied by an adaptive algorithm [2] for a total of ~80 trials per condition (depending on availability of each child, as reported in Table S1). The control group data were taken from our previous study [1].

*Correspondence: monica.gori@iit.it

The proportion of trials where the probe was judged to be taller or more slanted than the standard was computed for each probe height and orientation. The resulting psychometric function was fit by cumulative Gaussian function, whose standard deviation (σ) estimated the discrimination threshold for that condition (thresholds measured for each child are reported in Table S1). Figures 1A and 1B show sample psychometric functions for a 7-year-old visually impaired subject (filled green circles) for haptic size and orientation discrimination (see Figure S1 for other examples), compared with those of normally sighted age-matched children (open black squares). The size discrimination functions are steep and orderly, yielding thresholds similar to age-matched controls. The orientation data, however, are disorderly, with only a shallow dependence on orientation, yielding a far greater threshold in the visually impaired subject than in the age-matched control.

The results for all 17 congenitally visually impaired children are shown in Figure 1C for size and Figure 1D for orientation. For size discrimination, the visually impaired (colored symbols) were slightly better on average than controls ($t(16) = 3.5$, $p < 0.002$, two-tailed), but for orientation discrimination they were far worse ($t(16) = 3.27$, $p < 0.003$, two-tailed), by an average factor of 2.2. There is a tendency for the difference between visually impaired and visually normal participants to diminish with age, but it does not vanish because even older children show worse orientation discrimination than controls. Orientation (but not size) thresholds are correlated with visual acuity, with lowest acuity corresponding to poorest orientation thresholds ($R^2 = 0.24$, $p < 0.03$; see Figure S2). Figure 2 plots size thresholds (normalized by the average of age-matched controls) against normalized orientation thresholds. Most points lie in the lower right quadrant, implying slightly better-than-average size discrimination and worse-than-average orientation discrimination. The arrows at the axes show averages across the entire group, 2.2 ± 0.3 for orientation and 0.8 ± 0.06 for size. There is one clear exception to the pattern of results, shown by the green star. This is a child who had normal vision from birth but became severely visually impaired at about 32 months.

Discussion

A long-standing question in perception is how sensory systems become calibrated with physical reality. In his famous 300-year-old "Essay toward a new theory of vision," Berkeley [3] observed that vision has no direct access to attributes such as distance, solidarity, or "bigness," which become tangible only after they have been associated with the experience of touch (proposition 45): "touch educates vision," perhaps better expressed as "touch calibrates vision." This concept could explain why size discrimination thresholds are dominated by touch. But why are orientation thresholds dominated by vision? Perhaps Berkeley was not quite right, and touch does not always calibrate vision, but the more robust and hence more accurate sense for a particular perceptual task is the calibrator (as the more precise sense is the more important for sensory fusion [4, 5]). Accuracy is defined in absolute

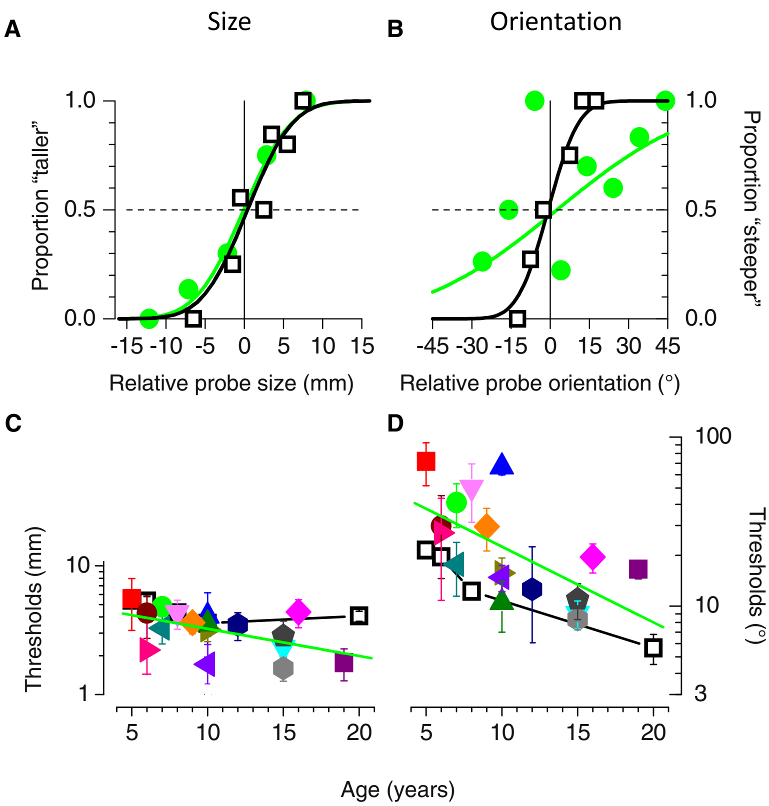

Figure 1. Individual Data for Haptic Orientation and Size Discrimination

(A) Example of a psychometric function for a nonsighted 7-year-old child (subject 2, filled green circles) and for a normally sighted age-matched child (open black squares) for haptic size discrimination, plotting proportion of trials where the test stimulus was judged to be taller than the standard as a function of test size. The data are fit with a cumulative Gaussian function whose standard deviation gives an estimate of size discrimination threshold (see also Figure S1A).

(B) Same as (A) but for orientation discrimination. The psychometric function for the nonsighted 7-year-old child (filled green circles) is far less steep, producing a threshold three times higher than the age-matched control (open black squares) (see also Figure S1B).

(C) Size discrimination thresholds for the visually impaired as a function of age. Each colored symbol represents a different subject (see Table S1 for more details), and the green line is the linear regression of these points. Open black symbols show the average of the typically sighted control group taken from publication [1]. Error bars on individual data points are ± 1 standard error of the mean (SEM) obtained by bootstrap [21], and those on the control data are ± 1 SEM of intersubject variability.

(D) Orientation discrimination thresholds for the visually impaired as a function of age, with the same symbol code as (C).

terms, as the distance from physical reality, whereas precision is a relative measure, related to the reliability or repeatability of the results: they are not necessarily the same (but are often correlated). It is therefore reasonable to suggest (but hard to prove) that for size, touch will be more accurate, because vision codes it indirectly via a complex calculation based on retinal size and estimation of distance. Orientation, on the other hand, may be represented more accurately by the visual than the haptic system. Although it is given only indirectly from haptic signals via complex coordinate transforms, for vision it may be a relatively more simple calculation from responses of orientation-selective cells in primary visual cortex [6], combined with a vestibular signal about head inclination. It seems reasonable to assume that this calculation is less problematic than that for size, where distance itself is not immediate.

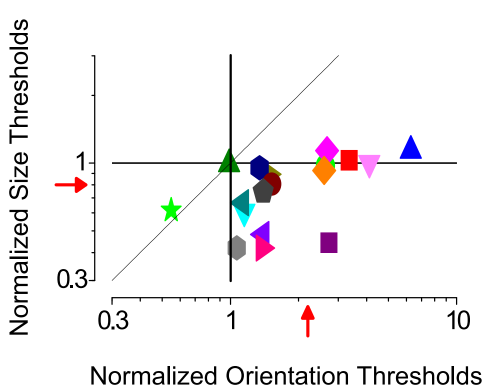

Figure 2. Individual Normalized Haptic Thresholds

Individual orientation thresholds normalized by the age-matched controls, plotted against normalized size thresholds, with the same symbol code as in Figures 1C and 1D. The thresholds were normalized by dividing each value reported in Figures 1C and 1D and Table S1 by the average age-matched control, obtained by interpolating the average thresholds for typical vision (black lines in Figures 1C and 1D). Most points lie in the lower right quadrant, implying better size and poorer orientation discrimination (see also Figure S2). The arrows refer to group averages, 2.2 ± 0.3 for orientation and 0.8 ± 0.06 for size. The green star in the lower left quadrant is the acquired low-vision child.

Several studies have demonstrated that cross-sensory calibration does occur in various situations where the information of one sense may be insufficient or conflictual (e.g., [4, 7, 8]). Our idea differs slightly from those of these authors who assumed, explicitly or implicitly, that the more precise sense calibrates the other. Because accuracy is often correlated with precision, the two are often difficult to tease apart. One exception is a recent study [9] showing that for audiovisual synchrony adaptation, the less-precise sense (vision) seems to be the calibrator. The authors suggest that although, for timing tasks, visual information is less precise than auditory information, it does not suffer from the systematic distance-dependent inaccuracies of sound and is therefore more accurate and appropriate for calibration.

We have previously suggested [1] that touch calibrates vision for size judgments but vision calibrates touch for orientation. Calibration is probably necessary at all ages, but during the early years of life, when children are effectively learning to see, reach, and grasp, calibration may be expected to be more important. It is during these years that limbs are growing rapidly and eye length and eye separation are increasing, all necessitating constant recalibration between sight and touch. Indeed, many studies suggest that the first eight years in humans correspond to the critical period of plasticity for many properties such as binocular vision [10] and acquiring accent-free language [11]. The mechanism of calibration remains unknown, but there exists good evidence from imaging and transcranial magnetic stimulation studies for cross-sensory interactions between vision and touch, particularly in haptic discrimination of orientation [12].

A strong prediction from the calibration hypothesis is that early impairment of the sense required for calibration should impact on the sense being calibrated. Specifically, haptic impairment should lead to poor visual size discrimination, and visual impairment should lead to poor haptic orientation discrimination. We tested and verified the latter of these predictions: haptic orientation thresholds were far worse in visually impaired subjects than controls, by more than a factor of 2 on average, whereas size discrimination was actually better than controls by a factor of 1.25.

Many previous studies have examined haptic perception in the visually impaired with seemingly contradictory results: some studies show the performance of blind and low-vision subjects to be as good or better than normally sighted controls in tasks such as size discrimination with a cane [13], haptic object exploration and recognition [14], and tactile recognition of 2D angles and gratings [15], whereas other tasks, including haptic orientation discrimination [16], visual spatial imagination [17], and representation and updating of spatial information [18], have shown impairments. Visually impaired children had particular difficulties with rotated object arrays [19]. And most recently, Dopjans and colleagues (2009, 10th International Multisensory Research Forum, abstract) have shown that congenitally blind subjects are worse than both blindfolded sighted and acquired-blind subjects at haptic recognition of faces. It is possible that the key to understanding the discrepancy in the literature is whether the haptic task may have required an early crossmodal visual calibration.

Of our sample of 18 subjects, there was one clear exception with orientation thresholds better than the controls. This subject had good vision until the age of about 32 months. Such patients are (fortunately) very rare in Italy, so we were unable to confirm this result on others, but we presume that the fine orientation thresholds in this subject result from the early visual experience (before 2.5 years of age), which may have been sufficient for the visual system to calibrate touch. Note that at this age, the haptic system is still not mature [1]. However, early exposure to vision seems to be sufficient to calibrate the developing haptic system, suggesting that the sensitive period for damage is shorter than that for normal development. This is consistent with other evidence for multiple sensitive periods, such as global motion perception [20].

The suggestion that specific perceptual tasks may require crossmodal calibration during development could have practical implications, possibly leading to improvements in rehabilitation programs. Where cross-sensory calibration has been compromised, for example by blindness, it may be possible to train people to use some form of "internal" calibration or to calibrate by another modality such as sound.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures, two figures, one table, and one movie and can be found with this article online at doi:10.1016/j.cub.2009.11.069.

Acknowledgments

We thank all of the children for their willing participation in this research, and the Istituto David Chiossone of Genova (in particular E. Cocchi and W. Sannita) and Fondazione Robert Hollman of Padova (in particular D. Nicchio and P. Caldironi) for their enthusiastic collaboration with this research. This project is partially supported by European Research Council "Ideas" grant "Space, Time and Number in the Brain" to D.B.

Received: August 3, 2009
Revised: November 20, 2009
Accepted: November 21, 2009
Published online: January 28, 2010

References

1. Gori, M., Del Viva, M., Sandini, G., and Burr, D.C. (2008). Young children do not integrate visual and haptic form information. Curr. Biol. *18*, 694–698.
2. Watson, A.B., and Pelli, D.G. (1983). QUEST: A Bayesian adaptive psychometric method. Percept. Psychophys. *33*, 113–120.
3. Berkeley, G. (1963). An essay towards a new theory of vision. In Works on Vision, C.T. Murray, ed. (Indianapolis, IN: Bobbs-Merril), pp. 19, (Originally published in 1709).
4. Ghahramani, Z., Wolpert, D.M., and Jordan, M.I. (1997). Computational models of sensorimotor integration. In Self-Organization, Computational Maps and Motor Control, V. Sanguineti and P.G. Morasso, eds. (Amsterdam: Elsevier), pp. 117–147.
5. Ernst, M.O., and Banks, M.S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. Nature *415*, 429–433.
6. Hubel, D.H., and Wiesel, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex. J. Physiol. *195*, 215–243.
7. Epstein, W. (1975). Recalibration by pairing: A process of perceptual learning. Perception *4*, 59–72.
8. Atkins, J.E., Jacobs, R.A., and Knill, D.C. (2003). Experience-dependent visual cue recalibration based on discrepancies between visual and haptic percepts. Vision Res. *43*, 2603–2613.
9. Navarra, J., Hartcher-O'Brien, J., Piazza, E., and Spence, C. (2009). Adaptation to audiovisual asynchrony modulates the speeded detection of sound. Proc. Natl. Acad. Sci. USA *106*, 9169–9173.
10. Banks, M.S., Aslin, R.N., and Letson, R.D. (1975). Sensitive period for the development of human binocular vision. Science *190*, 675–677.
11. Doupe, A.J., and Kuhl, P.K. (1999). Birdsong and human speech: Common themes and mechanisms. Annu. Rev. Neurosci. *22*, 567–631.
12. Zangaladze, A., Epstein, C.M., Grafton, S.T., and Sathian, K. (1999). Involvement of visual cortex in tactile discrimination of orientation. Nature *401*, 587–590.
13. Sunanto, J., and Nakata, H. (1998). Indirect tactual discrimination of heights by blind and blindfolded sighted subjects. Percept. Mot. Skills *86*, 383–386.
14. Morrongiello, B.A., Humphrey, G.K., Timney, B., Choi, J., and Rocca, P.T. (1994). Tactual object exploration and recognition in blind and sighted children. Perception *23*, 833–848.
15. Alary, F., Duquette, M., Goldstein, R., Elaine Chapman, C., Voss, P., La Buissonnière-Ariza, V., and Lepore, F. (2009). Tactile acuity in the blind: A closer look reveals superiority over the sighted in some but not all cutaneous tasks. Neuropsychologia *47*, 2037–2043.
16. Postma, A., Zuidhoek, S., Noordzij, M.L., and Kappers, A.M. (2008). Haptic orientation perception benefits from visual experience: Evidence from early-blind, late-blind, and sighted people. Percept. Psychophys. *70*, 1197–1206.
17. Noordzij, M.L., Zuidhoek, S., and Postma, A. (2007). The influence of visual experience on visual and spatial imagery. Perception *36*, 101–112.
18. Pasqualotto, A., and Newell, F.N. (2007). The role of visual experience on the representation and updating of novel haptic scenes. Brain Cogn. *65*, 184–194.
19. Ungar, S., Blades, M., and Spencer, C. (1995). Mental rotation of a tactile layout by young visually impaired children. Perception *24*, 891–900.
20. Lewis, T.L., and Maurer, D. (2005). Multiple sensitive periods in human visual development: Evidence from visually deprived children. Dev. Psychobiol. *46*, 163–183.
21. Efron, B.T., and Tibshirani, R.J. (1993). An Introduction to the Bootstrap (New York: Chapman & Hall).