Spatial Cognition & Computation, 12:83–95, 2012

ISSN: 1387-5868 print/1542-7633 online
DOI: 10.1080/13875868.2011.599901

Taylor & Francis
Taylor & Francis Group

A Review of Haptic Spatial Abilities in the Blind

Valerie Morash,[1] Allison E. Connell Pensky,[1] Andrea Urqueta Alfaro,[1] and Amanda McKerracher[1]

[1]University of California–Berkeley, Berkeley, California, USA

Abstract: We review evidence of spatial abilities in the blind and address proposed limitations of haptic perception (the combination of tactile, proprioceptive, and kinesthetic information) in forming spatial representations. In particular, we counter the idea that touch is sequential and permits only egocentric representations. We consider specific spatial abilities of the blind with regards to development, and two-dimensional depictions of space. We conclude that spatial capacities in the blind are not diminished compared to those of the sighted.

Keywords: blind, haptic, spatial perception, navigation, development

1. INTRODUCTION

Spatial abilities of the blind have long been of interest to philosophers and researchers. How we come to understand space and how we know where objects and persons are within that space is addressed by considering the perception of, and interactions with, space. Emerging from this is a debate over the importance of vision versus haptics (i.e., the combination of tactile, proprioceptive, and kinesthetic information), two senses that provide a great deal of information about objects and their spatial relationships with one another. This is where an interest in blind people's spatial abilities originates; if the blind are unable to perceive or represent some aspect of space, then it is evident that vision is a necessary sense for spatial tasks. Here, we follow the historical precedent of examining haptic spatial abilities in the blind. However, it is important to note that binaural auditory perception and locomotion also provide spatial information to the blind, although these are beyond the scope of this review.

Few people have been as pessimistic about spatial abilities of the blind as Lotze (1884), who proposed that space was a visual phenomenon and beyond

Correspondence concerning this article should be addressed to Amanda McKerracher, 4511 Tolman Hall, University of California–Berkeley, Berkeley, CA 94720. E-mail: mckerracher@berkeley.edu

comprehension by the blind. Instead of space, the blind man would experience "an artificial system of conceptions of movement, time, and effort" (p. 500). This idea was later supported by von Senden (1960), who reviewed cases where sight was restored by cataract removal. In four people with weak pre-operation light sense, von Senden determined that the blind had no concept of space. One man had a "schema" of space, but when his vision was restored it was clear that this "substitute-space" was nothing like real space as revealed by sight. von Senden reviewed many other cases of blind individuals, finding that spatial concepts were much clearer after sight restoration. This led him to conclude, "true awareness of space can be given only by sight and not by touch" (p. 78).

In hindsight, the proposal that blind people cannot comprehend space is unreasonable. In our society, we observe blind people walking about town and manipulating objects, neither of which would be possible without an understanding of space.

2. VIEWS ON SPATIAL ABILITIES OF THE BLIND

Although Lotze (1884) and von Senden's (1960) extremely negative view of blind people's spatial abilities has been dismissed, several limitations have been proposed. With respect to touch, two limitations have been proposed: the low spatial acuity of touch, and the claim that touch is "sequential" (also referred to as "serial" and "successive"). These complaints have been used to support the idea that, although a spatial understanding *can* be gained through touch, it is rough and piecemeal compared to that gained through vision (Révész, 1950; Warren, 1984). The proposed limitation due to spatial acuity is not strong, because tactile acuity is not low enough to prohibit the discrimination of spatial relationships, at least between objects. The notion that touch is sequential has more support, and requires more consideration.

William James (1890) provided perhaps the earliest mentions of the sequential nature of touch and simultaneous nature of vision. He explained that a "seeing baby's eyes take in the whole room at once" which must then be analyzed to discern individual objects, whereas the blind child "must form his mental image of the room by the addition, piece to piece, of parts which he learns to know successively" (p. 203). James provided no empirical evidence to support his claim. Later, von Senden (1960) reviewed cases of blind individuals and concluded that "concerning simultaneous touch we do not in fact find any generally applicable evidence" (p. 43) but "there are many examples in our sources of the successive touching of larger objects which cannot be encompassed all at one time" (p. 44). The successive nature of touch also appeared in the influential work by Révész (1950), again with little empirical evidence. Citations attesting to the successive nature of touch often reference these early scholars without acknowledging that they were based on, at best, tenuous and subjective evidence.

In contrast, simultaneous perception (associated with minimal hand movements) of two-dimensional depictions can be achieved when the design is within the size of the fingertip (e.g., Braille letters). Additionally, when objects fit within the hand, sequential procedures are unnecessary. For example, Davidson (1972) and Davidson and Whitson (1974) asked blind and sighted people to make judgments about whether a curve was concave or convex. Sighted participants adopted an error-prone method of using one or two fingers to trace along the curve. In contrast, blind participants applied their entire hand to the curve, and thereby used simultaneous perception to achieve higher accuracy. Movement in touch may be necessary when perceiving certain object characteristics, such as texture (Lederman, 1982), however this type of movement is not the same as the large movements used to support the notion of sequential perception. The movement from part-to-part observed when touching an object is similar to the behavior of moving from place-to-place to see areas beyond view. Touch is sequential only for objects that are large relative to the field of touch, like vision is sequential for objects that are large relative to the field of view.

In fact, vision is arguably sequential even with objects contained within the field of view. The act of looking at an object or scene involves saccades, eye jumps, from one part to another (Yarbus, 1967). The eyes do not sit fixed at the center of the image, taking in the scene all at once, nor do they smoothly sweep the scene. The difference between the visual saccades and movements of the hand is that the saccades are rapid whereas the hand is slow. Given enough time, recognition of objects based on touch can be raised to the accuracy based on vision (Davidson, Abbott, & Gershenfeld, 1974).

Considering evidence that vision and touch are similarly sequential raises the question of whether it matters if a sensory system is sequential or simultaneous for the resulting representation. The procedural operations used for sensation do not mandate the representation formed from these sensations. Hence, sequential movement of the hand or eye over an object does not necessarily result in a fragmented representation (Lopes, 2003).

Another limitation attributed to touch is that it can only be used to perceive objects in an egocentric, or body-centric, reference frame (see Cattaneo, 2008). In contrast, vision can make use of egocentric and allocentric, object-centric or global, reference frames. This idea may originate from von Selden (1960) and others, who assumed that the blind man's spatial awareness was in reference to his body. For example, "near" was when an object touched the skin and "far" was when it did not. However, the most pervasive argument is that when viewing an object, peripheral vision anchors the object to objects around it, facilitating allocentric representation. Because the field of touch is small relative to the field of view, an object that is felt cannot be similarly anchored to objects around it, and an egocentric representation must be adopted (Révész, 1950).

The proposal that the field of touch is small is strongest when a single finger is used, or the fingers are held close together. Symmons and Richardson

(2000) found that blindfolded-sighted people would explore some types of raised-line drawings with a single finger a large proportion of the time. However, this may be the result of the stimuli, the participants performing according to perceived expectation, or the relatively little training and experience sighted people have relying on touch without vision. Contrary to these findings, blind people using tactile maps will often adopt a multifinger or multihand strategy (Perkins & Gardiner, 2003).

As might be expected, using more than one finger facilitates the formation of allocentric reference frames. Millar and Al-Attar (2004) explicitly asked their participants to use one hand to examine a route on a raised-line map, and the other hand to trace the border of the map. By tracing the border, participants encoded the map routes in an allocentric, rather than egocentric, reference frame. Overall, it appears that allocentric reference frames can be used in touch (see also, Kappers, 2007), but particular reference frames in touch may only be adopted when using specific strategies, especially the use of multiple fingers (Millar & Al-Attar, 2004; Ballesteros, Millar, & Reales, 1998).

Provided that touch is not limited to successive and egocentric representations, it is to be expected that equivalent spatial representations can arise from touch and vision. Recently, Giudice, Betty, and Loomis (2011) reported that touch and vision provide similar spatial representations of a map. The researchers asked participants to learn maps either visually or haptically, and then did or did not disrupt the participant's egocentric or allocentric relationship to the map. Participants were then asked to imagine standing at a particular location on the map, and then turn in place to face a final map location. Errors of the final turn were not significantly different for maps learned through vision and touch for all conditions, indicating that similar, if not equivalent, map representations had been formed through the two senses.

The historical evolution of arguments against spatial perceptions and representations from touch, and in favor of those from vision, may indicate the slow acceptance of the functional equivalence of these two senses. For example, Held et al. (2011) recently conducted a study similar to those reviewed by von Senden (1960), in which sight was restored following congenital blindness. Held et al. found that visual-haptic transfer of shape information was not possible immediately after vision restoration, but occurred within a few days. In contrast to von Senden's results, Held et al. concluded that their blind participants had an operational haptic spatial representation that was quickly mapped onto the visual sense.

As researchers continue to determine whether there are spatial deficits associated with touch, they have transitioned from the most extreme to more specific arguments, and may eventually arise at a particular deficit of touch in extracting some spatial datum. For example, it has been proposed that touch may be more analytic and vision more global (Gentaz & Hatwell, 2003), or touch may focus on local features and vision on aggregate features (Avizzano, Frisoli, & Bergamasco, 2008). However, it is more likely that touch specializes in extracting some types of information from the environment (e.g., material properties such as texture) and vision others (e.g., shape and space), not born from the incapacity of touch to extract spatial information but due to efficiency. Touch may be slower than vision at extracting spatial information, but is not inferior in the representations it produces.

3. SPATIAL DEVELOPMENT IN BLIND CHILDREN

According to Piaget (1954), space representation is constructed based on the child's perceptions and actions in his environment. The development of the concept of space is correlated with the development of object concept, or object permanence, because for the child to progressively understand that objects exist independently from him, he has to adopt an allocentric perspective. In other words, he has to conceive of the object within a space where he himself is an object among others and in which all objects can move independently.

In Piaget's (1954) words "only the degree of objectification that the child attributes to things informs us of the degree of externality he accords to space" (p. 99). Interacting with space plays a significant role in Piaget's view; reaching allows the child to make a practical distinction between near space (i.e., objects that can be grasped) and distant space (i.e., objects that cannot be grasped without involving locomotion). With locomotion the child is eventually able to perceive planes of depth. Thus, Piaget postulated that concepts are not innate, nor directly perceived, but the result of a process of mental constructions of representations based on interactions with the environment.

In contrast, Gibson (1969) proposed that a child directly perceives space from the environmental information gained through his senses. In her theory vision plays a distinctive role, and as the child develops he becomes able to perceive features in any sensory modality. Here again, the child's actions on the environment are of great importance, as perceiving is acting in the environment. It is through actions that affordances (i.e., those properties of the environment that are suited for direct perception) are learned. Infants are not endowed with perception of affordances, and most of their first year of life entails learning how to extract information from stimulation in their environment, which requires exploring it (Gibson, 1969, 1988). Thus, even though the space concept is not constructed, experience acting in the environment does play a role in understanding space.

From either perspective, congenitally blind children's perception of space is thought to be impaired in a number of ways. Visual information is critical within both theories. For Piaget, visual cues are essential for the intertwined development of space and object concepts. These depend on the child being able to manipulate objects and thus observe the objects in different positions, as partially or fully covered, from different perspectives, and having different sizes. For Gibson, vision plays a unique role among all the senses; impairments in vision would be extremely detrimental given that development happens through perceptual learning of visual affordances. However, Gibson's idea that with development, children learn to abstract amodal features implies that blind children could eventually perceive space using their intact senses.

In addition to visual cues, both theories stress the role of acting in the environment. Congenitally blind children show a significant delay in reaching (7–12 months according to Fraiberg, 1968; 13–32 months according to Bigelow, 1986) compared to sighted children (5 months). This delay has been used to propose that blind children are delayed in their spatial and object permanence understanding compared to sighted children. Bigelow (1986) provides an alternative explanation for this delay in line with Piaget's perspective: unlike sighted children, who start reaching in response to seeing interesting objects, blind children must first achieve a certain understanding of object concept before they can start reaching on a sound cue. Additionally, sighted children reliably reach on sound cues (10 months) later than they do on vision cues (5 months). Therefore, blind children are not delayed compared to sighted children in reaching to spatial locations using their available sense of hearing.

This finding illustrates the need take caution when comparing blind and sighted children. This type of comparison has supported the idea that space perception is delayed or impoverished in blind children. Instead of comparing the blind child to his sighted peers, one should investigate the developmental trajectory that is normative for the blind child. The former comparison leads to blind children being characterized by what is missing in them, while in the latter approach blind children's development is considered as a unique pathway given their non-visual access to the world. A blindfolded-sighted person is not equivalent to a blind person, and the way haptic and auditory cues work may differ between these groups (Warren, 1984). Furthermore, blind and sighted children will have qualitatively different experiences, shaped by their interactions with the environment and people (e.g., teachers and parents) who may have expectations regarding the child's abilities.

Additionally, research on blind infants must be understood in combination with research on blind adults. The fact that many blind adults can successfully and independently navigate their environments supports Vygotsky's (1993) view that visually-impaired children achieve the same level of development as sighted children, albeit through qualitatively different processes.

Despite these considerations, some specific delays in the blind when compared to the sighted are logically expected and supported by empirical data. For instance, in a longitudinal study that compared blind and sighted children, Bigelow (1996) found that blind children showed a delay in using the overall layout of their homes when compared to sighted peers. These blind children used their knowledge of routes when judging straight-line distances between familiar locations until 12–13.5 years of age, when they started using overall layout. Sighted children did so by 8–9 years of age. This is clear evidence of sophisticated spatial representations by the blind of their environment, albeit delayed.

The literature reviewed here demonstrates that some aspects of blind children's spatial development are normal when compared to the sighted (e.g., reaching towards a sound cue). Ultimately, blind children do develop an understanding of their spatial environment, but through qualitatively different means than their sighted peers.

4. BLINDNESS AND DEPTH IN TWO-DIMENSIONAL DEPICTIONS

A large effort in vision research has been made to understand how vision allows the perception and representation of space through depth. Many of the cues used in vision to represent depth, such as perspective and occlusion, can be portrayed in images. Using raised-line drawings, where lines on a page are raised allowing tactile perception, these visual depth cues have been presented to the blind. Many researchers and practitioners have spoken out against the presence of visual depth cues in raised-line drawings, explaining that these visual representations of depth are not appropriate for the blind (e.g., Edman, 1992). However, others, most notably Kennedy (e.g., Kennedy, 1993), argue that blind people can understand spatial relationships indicated by pictorial depth cues, and these cues can be learned naturally by touch as they can with vision. Here, we will introduce the depth cues in question, discuss their derivation from vision and touch, and consider how the sighted and blind learn to use these cues.

4.1. Visual Depth Cues in Line Drawings

Line drawings can only portray a small fraction of the pictorial depth cues (those that can be portrayed in an image) provided to vision. Line drawings can indicate depth using occlusion, linear perspective, relative/familiar size, distance from the horizon, and texture gradient (see Palmer, 1999). The line-based pictorial depth cues arise in vision mandated by the geometry of light as it travels from the environment to the observers' eyes (perspective projection). Occlusion is caused when an object blocks the light reflected from another object on its path to the eyes, with the blocked (occluded) object further away from the observer than the occluding object.

Receding parallel lines in the environment are no longer parallel once projected onto the retina, instead they converge towards a vanishing point on the horizon as they move further from the observer, referred to as linear perspective. The diminishing distance between the parallel lines as they move away is not unique to linear perspective; all objects decrease in size on the retina as they are further from the observer, called relative/familiar size. The parallel lines also approach the horizon as they recede in depth, which is again not unique to linear perspective. Objects closer to the horizon on the retinal image are further from the observer. Finally, texture gradient combines many of these cues. Imagine looking down a cobblestone road. As the road gets further away, the parallel columns of stones will converge as in linear perspective, the far stones will be smaller and closer to the horizon than the close ones, and the details of the close stones will be more discernible than those of the far stones. These attributes are all part of texture gradient.

4.2. Sighted People Learning Depth Cues in Line Drawings

There is converging evidence that the line-based pictorial depth cues are learned by sighted people young in life, without instruction, and without prior exposure to line drawings. Sighted infants perceive the line-based pictorial depth cues very early. For example, Baillargeon and DeVos (1991) showed 3.5-month-old infants two carrots, one that violated the rules of occlusion and one that did not. Infants looked longer at the occlusion-violating carrot, demonstrating their understanding of occlusion. In an earlier study, Yonas, Granrud, and Pettersen (1985) demonstrated that 5.5-month-olds preferentially reached for a larger toy than a smaller toy, presumably because they believed it to be closer. Similarly, Yonas, Elieff, and Arterberry (2002) showed infants two identical toys positioned in front of a screen portraying a surface receding into the distance using linear perspective and texture gradient. By 7 months, infants preferentially reached for the lower (closer) toy. In the studies by Yonas and colleagues, these effects were only observed when the infant had one eye covered. With both eyes, infants could determine that toys were equidistant and showed no preference.

These developmental studies demonstrate that learning line-based pictorial depth cues occurs early in life for sighted children, but do not demonstrate that this learning could take place without instruction. Hochberg and Brooks (1962) tested a child that had been raised with little exposure to pictures. The child's environment was largely stripped of pictures, and he was never instructed about pictures or given feedback on the occasion he encountered a picture and attempted to name it. At 19 months, the child was shown several images, including a line drawing of a car and a doll that contained self-occlusion, linear perspective, and relative/familiar size. The child had no trouble in naming these items.

The aforementioned studies are not conclusive on whether the line-based pictorial depth cues can be learned without exposure to images, as the infants had some exposure to line and photographic depictions. Kennedy and Ross (1975) examined how the Songe, isolated native peoples of New Guinea, interpreted line drawings with depth cues. The Songe had essentially no indigenous graphic art, and had not developed drawing conventions that would impede their interpretation of Western drawings. Among the images shown to the Songe were ones that included occlusion, relative/familiar size, and distance from the horizon, all of which were correctly interpreted by the Songe.

4.3. Depth Cues in Raised-Line Drawings

Line-based pictorial depth cues are sometimes considered inappropriate for raised-line drawings because these depth cues result from the projection of light onto the two-dimensional retina, a process that does not occur for the blind observer. However, opponents of this view have pointed out that at least two of these depth cues—occlusion and linear perspective—have a haptic interpretation.

Occlusion has a derivation in touch similar to that in vision: an occluder can block the touching of an object behind it (Kennedy, 1993). In vision, the occluder absorbs light bouncing off of the occluded object before it reaches the observer. In touch, the occluder blocks the arm reaching out from the observer before it reaches the occluded object. These opposite sequences may lead to differences in how a scene is depicted. For example, some blind people will draw objects in a "folded out" fashion, where all sides of an object are depicted (like the globe is folded out on a map). This is reasonable, because with vision self-occlusion results in only one or a few sides being visible, whereas with touch the hand is exposed to all sides of the object by wrapping around it (Lambert and Lederman, 1989; Edman, 1992; Kennedy, 1993).

Linear perspective can also be derived from haptic information. Descartes (2001) explained that a blind person holding a stick in each hand could place the distal ends of the sticks on an object. From the angles that the sticks were pointed inwards, the blind man could deduce the distance of the object. Similarly, Kennedy (1993) showed that by pointing to the near and far corners on the floor of a room, a blind person could deduce which set was farther by the smaller angle between the arms.

Although a haptic derivation has not been suggested for relative/familiar size, distance from the horizon, and texture gradient, the existence of haptic derivations for occlusion and linear perspective suggest that line-based pictorial depth cues may be reasonable representations of space for the blind.

4.4. Blind People Learning Depth Cues in Line Drawings

In general, it is better to consider the perception rather than the production of line drawings to establish whether a person can understand a depth cue, due to the fact that producing a drawing requires abilities beyond perception, most notably motor control. Unfortunately, relative to vision research, far less research has been conducted about touch, let alone the tactile perceptions of the blind. Of what has been done, a large proportion of the research on congenitally blind people relies on their drawings. These studies suggest that the blind need training to draw with occlusion. Although some blind people will draw with occlusion, many will not (Kennedy, 1993). It is not always clear how much training has been administered.

Research on perception, rather than drawing, is sparser, but clearer. To depict a tactile texture gradient, Holmes, Hughes, and Jansson (1998) created an array of raised dots that got smaller and closer together, and were in columns that converged, to depict a surface slanted backwards by varying degrees. The researchers observed that both blindfolded-sighted and blind people could use the tactile texture gradient to perceive a depiction of slant, but only after training. With no training, depth was not understood from the tactile texture gradient.

Similarly, blind observers can become confused and need clarification as to what perspective in raised-line drawings may represent. However, they can be taught to recognize perspective and use it as spatial information (Heller, 2002; Heller, Kennedy, Clark, et al., 2006).

Research indicates that some, but not all of the line-based pictorial depth cues are discoverable through touch, but most blind people must be explicitly taught what these cues represent in raised-line drawings. Therefore, the portrayal of depth in two dimensions by way of these depth cues is an appropriate spatial representation in vision but not touch. This is of particular importance in the selection of tactile stimuli. However, this in no way questions the value of raised-line drawings for the blind as a form of expression, educational supplements to textbooks, and educational depictions of vision-based terminology.

5. GENERAL DISCUSSION

This review has focused on haptic representations of space among blind persons. We have countered supposed limitations, reviewed literature on spatial development, and examined pictorial depth cues in raised-line drawings. From these sources of evidence, we are able to conclude that the blind can and do perceive and represent space in a functionally equivalent, but qualitatively different manner from the sighted.

This conclusion has implications beyond those for the blind. It challenges a central tenet of embodiment theory, that "the same neural and cognitive mechanisms that allow us to perceive and move around also create our conceptual systems and modes of reason" (Lakoff & Johnson, 1999, p. 4). This theory would predict functional differences between blind and sighted people in spatial perceptions and representations. The evidence reviewed herein supports an alterative conclusion, that blind and sighted individuals can have functionally equivalent perceptions and representations of space from the haptic sense.

REFERENCES

Avizzano, C. A., Frisoli, A., & Bergamasco, M. (2008). Design guidelines for generating force feedback on fingertips using haptic interfaces. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 393–410). Boston, MA: Birkhäuser Verlag.

Baillargeon, R., & DeVos, J. (1991). Object permanence in young infants: Further evidence. *Child Development, 62,* 1227–1246.

Ballesteros, S., Millar, S., & Reales, J. (1998). Symmetry in haptic and in visual shape perception. *Attention, Perception, & Psychophysics, 60*, 389–404.

Bigelow, A. (1986). The development of reaching in blind children. *British Journal of Developmental Psychology, 4,* 355–366.

Bigelow, A. E. (1996). Blind and sighted children's spatial knowledge of their home environments. *International Journal of Behavioral Development, 19,* 797–816.

Cattaneo, Z., Vecchi, T., Cornoldi, C., Mammarella, I., Bonino, D., et al. (2008). Imagery and spatial processes in blindness and visual impairment. *Neuroscience and Biobehavioral Reviews, 8,* 1346–1360.

Davidson, P. W. (1972). Haptic judgments of curvature by blind and sighted humans. *Journal of Experimental Psychology, 93*, 43–55.

Davidson, P. W., Abbot, S., & Gershenfeld, J., (1974). Influence of exploration time on haptic and visual matching of complex shape. *Perception & Psychophysics, 15,* 539–543.

Davidson, P. W., & Whitson, T. T. (1974). Haptic equivalence matching of curvature by blind and sighted humans. *Journal of Experimental Psychology, 102*, 687–690.

Descartes, R. (2001). *Discourse on method, optics, geometry, and meteorology*. (P. J. Olscamp, Trans.) Indianapolis: IN: Hackett Publishing Company.

Edman, P. K. (1992). *Tactile graphics.* New York, NY: American Foundation for the Blind.

Fraiberg, S. (1968). Parallel and divergent patterns in blind and sighted infants. *Psychoanalytic Study of the Child*, *23,* 264–300.

Gentaz, E., & Hatwell, Y. (2003). Haptic processing of spatial and material object properties. In Y. Hatwell, A. Streri, & E. Gentaz (Eds.), *Touching for knowing* (pp. 123–159). Philadelphia, PA: John Benjamins.

Gibson, E. J. (1969). *Principles of perceptual learning and development*. New York, NY: Appleton-Century-Crofts.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving acting and the acquiring of knowledge. *Annual Review of Psychology, 39,* 1–41.

Giudice, N. A., Betty, M. R., & Loomis, J. M. (2011, February 7). Functional equivalence of spatial images from touch and vision: Evidence from spatial updating in blind and sighted individuals. *Journal of Experimental*

Psychology: Learning, Memory, and Cognition. Advance online publication.

Held, R., Ostrovsky, Y., de Gelder, B., Gandhi, T., Ganesh, S., Mathur, U., & Sinha, P. (2011). The newly sighted fail to match seen with felt. *Nature Neuroscience, 14,* 551–554.

Heller, M. A. (2002). Tactile picture perception in sighted and blind people. *Behavioral Brain Research, 135,* 65–68.

Heller, M. A., Kennedy, J. M., Clark, A., McCarthy, M., Borgert, A., Fulkerson, E., Wemple, L. A., Kaffel, N., Duncan, A., & Riddle, T. (2006). Viewpoint and orientation influence picture recognition in the blind. *Perception, 35,* 1397–1420.

Hochberg, J., & Brooks, V. (1962). Pictorial recognition as an unlearned ability: A study of one child's performance. *American Journal of Psychology, 75*, 624–628.

Holmes, E., Hughes, B., & Jansson, G. (1998). Haptic perception of texture gradients. *Perception, 27*, 993–1008.

James, W. (1890). *The principles of psychology, Volume 2.* New York, NY: William Holt and Company.

Kappers, A. M. L. (2007). Haptic space processing: Allocentric and egocentric reference frames. *Journal of Experimental Psychology, 61,* 208–218.

Kennedy, J. M. (1993). *Drawing and the blind: Pictures to touch*. New Haven, CT: Yale University Press.

Kennedy, J. M., & Ross, A. S. (1975). Outline picture perception by the Songe of Papua. *Perception, 4*, 391–406.

Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to Western thought.* New York, NY: Basic Books.

Lambert, L., & Lederman, S. (1989). An evaluation of the legibility and meaningfulness of potential map symbols. *Journal of Visual Impairment & Blindness, 83,* 397–403.

Lederman, S. J. (1982). The perception of texture by touch. In W. Schiff & E. Foulke (Eds.), *Tactual perception: A sourcebook* (pp. 130–167). New York, NY: Cambridge University Press.

Lopes, D. M. M. (2003). Are pictures visual? A brief history of an idea. In E. Axel & N. Levent (Eds.), *Art beyond sight* (pp. 176–185). New York, NY: AEB and AFB Press.

Lotze, H. (1884). *Metaphysic: In three books, ontology, cosmology, and psychology.* Oxford, England: Clarendon Press.

Millar, S., & Al-Attar, Z. (2004). External and body-centred frames of reference in spatial memory: Evidence from touch. *Perception and Psychophysics, 66*, 51–59.

Palmer, S. E. (1999). *Vision science: Photons to phenomenology*. Cambridge, MA: MIT Press.

Perkins, C., & Gardiner, A. (2003). Real world map reading strategies. *The Cartographic Journal, 40,* 265–268.

Piaget, J. (1954). *The construction of reality in the child*. New York, NY: Ballantine.

Révész, G. (1950). *Psychology and art of the blind.* (H. A. Wolff, Trans.). London: Longmans Green.

Symmons, M., & Richardson, B. (2000). Raised line drawings are spontaneously explored with a single finger. *Perception, 29*, 621–626.

von Senden, M. (1960). *Space and sight.* (P. Heath, Trans.). London, UK: Methuen (Original work published 1932).

Vygotsky, L. S. (1993). *The collected works of L. S. Vygotsky: The fundamentals of defectology*. R. W. Rieber & A. S. Carton (Eds.). New York, NY: Plenum Press.

Warren, D. (1984). *Blindness and early childhood development* (2nd ed.). New York, NY: American Foundation for the Blind.

Yarbus, A. L. (1967). *Eye movements and vision.* New York, NY: Plenum.

Yonas, A., Elieff, C. A., & Arterberry, M. E. (2002). Emergence of sensitivity to pictorial depth cues: Charting development in individual infants. *Infant Behavior and Development, 25*, 495–514.

Yonas, A., Granrud, C. E., & Pettersen, L. (1985). Infants' sensitivity to relative size information for distance. *Developmental Psychology, 21*, 161–167.