Cognitive Mechanisms of 2D-to-3D Spatial Information Transformation in Haptic 2D Image Recognition

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Abstract

Tactile 2D images constitute an important modality for visually impaired individuals to access graphical information. At present, most tactile 2D images are directly converted from visual 2D images into tangible line drawings. In visual 2D images, visual principles such as perspective and viewpoint are typically utilized to transform three-dimensional spatial relationships into two-dimensional planar relationships. Through extensive long-term perceptual learning, the visual system has acquired this 2D-to-3D mapping relationship. However, how the tactile system establishes a mapping between two-dimensional planes and three-dimensional space when recognizing 2D images through touch remains an open question for further research. The primary visual factors affecting 2D-to-3D spatial information conversion in tactile 2D image recognition include perspective, viewpoint, occlusion, texture gradient, and hollowness. When visual 2D images are directly converted into tactile 2D images, these visual factors contained within the images often interfere with tactile recognition. Building upon existing research, we propose a "Dual-Representation Processing Model" to explain the cognitive mechanism underlying the conversion from 2D to 3D spatial information during tactile exploration of 2D images. This model posits that tactile recognition of 2D images depends on the integration of two representation systems: an object representation system (involving object size, shape, and texture) and a spatial representation system (involving spatial relationships, perspective, and viewpoint of objects). Information from both representation systems is ultimately integrated, establishing a mapping between 2D images and 3D space based on successful matching between object representation and spatial representation, thereby accessing three-dimensional object representations in long-term memory. The Dual-Representation Processing Model will facilitate a deeper understanding of the cognitive mechanisms of tactile perception and provide a theoretical foundation for the design of tactile 2D images.

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Cognitive Mechanisms of 2D-to-3D Spatial Information Transformation in Haptic Recognition of 2D Images

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Abstract

Tangible two-dimensional (2D) images represent a crucial means for visually impaired individuals to access graphical information. Currently, most tactile 2D images are directly converted from visual 2D images into tangible line drawings. Visual 2D images typically employ perspective and viewpoint principles to transform three-dimensional (3D) spatial relationships into 2D planar representations. Through extensive perceptual learning, the visual system acquires this 2D-to-3D mapping relationship. However, how the haptic system establishes a mapping between 2D planes and 3D space when recognizing 2D images through touch remains an open research question. The primary visual factors affecting this 2D-3D spatial information transformation in haptic recognition include perspective, viewpoint, occlusion, texture gradient, and hollow-out. When visual 2D images are directly converted into tactile 2D images, these visual factors often interfere with haptic recognition. Building upon existing research, we propose a "dual-imagery processing model" to explain the cognitive mechanisms underlying 2D-to-3D spatial information transformation during haptic image exploration. This model posits that haptic recognition of 2D images depends on the integration of two imagery systems: an object imagery system (concerned with object size, shape, and texture) and a spatial imagery system (concerned with spatial relationships, perspective, and viewpoint). Information from these two systems ultimately integrates, establishing a mapping between 2D images and 3D space based on successful matching of object and spatial imagery, thereby accessing 3D object representations stored in long-term memory. The dual-imagery processing model will enhance our understanding of haptic perception mechanisms and provide theoretical guidance for tactile 2D image design.

Keywords: haptics, two-dimensional image, haptic recognition, perspective, viewpoint

Touch plays an irreplaceable role in human and animal survival. Primates, including humans, acquire tactile information when grasping objects to facilitate object use and manipulation (Sathian, 2016), and tactile sensations influence emotional experiences during object exploration (Kitada et al., 2021; Pasqualotto et al., 2020; Yasaka et al., 2019). The brain receives information through multiple sensory channels and integrates it to form multimodal representations (Lacey & Sathian, 2014; Perini et al., 2020). When visual information is insufficiently available—such as in cases of visual impairment or dark environments—touch serves as an important substitute for vision (Toprak et al., 2018).

According to statistics, in 2020 there were 399 million people with low vision globally, including 70.9 million individuals with total vision loss (Flaxman et al., 2017). Visually impaired individuals require tactile 2D images to learn visually-dependent subjects such as geometry, art, and geography (Bara et al., 2018; Cavazos Quero et al., 2021; Szubielska et al., 2019). Recent electronic tactile displays can present tangible 2D images in real-time and dynamically, potentially even enabling internet access for visually impaired users (Kim et al., 2019; Jiao et al., 2016; Lu & Zong, 2017). Multi-touch interactive data analysis systems developed specifically for tactile 2D image research can capture, analyze, encode, and interpret user behaviors during haptic tasks (Garcia et al., 2020). However, the 2D planar images generated by current products are all based on visual principles for presenting 3D objects and scenes, typically employing numerous visual cues—particularly monocular depth cues including perspective, viewpoint, occlusion, texture gradient, and hollow-out—to express depth and stereoscopic information (Lebreton, 2016), thereby transforming 3D spatial relationships into 2D planar relationships. Although the visual system can rapidly and effectively acquire depth information and 3D features through binocular disparity, monocular cues, and extensive perceptual learning with eye-hand coordination (Zhang & Li, 2020; Wang et al., 2020), research has found that both blindfolded sighted individuals and blind participants achieve only 30-40% accuracy when haptically recognizing 2D line drawings of natural objects (Sinha & Kalia, 2012). This suggests that visual factors such as perspective and viewpoint may hinder haptic recognition and cannot be directly transferred to tactile 2D image design (Bauer et al., 2015; Gong et al., 2018; Yu et al., 2019), resulting in low utilization rates of traditional paper-based tactile graphics and their production equipment (Jiao et al., 2016). Thus, despite mature tactile 2D image production technology, how to establish mapping between 3D space and vision-based 2D space during haptic recognition remains unclear. How to better design tactile 2D images and effectively improve recognition performance for visually impaired individuals remains an urgent problem. Therefore, investigating visual factors that affect haptic 2D image recognition is not only important for understanding haptic perception mechanisms but also provides theoretical guidance for tactile 2D image design.

This paper focuses on 2D-to-3D spatial information transformation in haptic 2D image recognition, examining visual modality-specific factors that reflect 2D-3D spatial mapping relationships, such as perspective and viewpoint. We review their effects on haptic 2D image recognition and analyze the underlying cognitive and neural mechanisms. Based on existing research, we propose a "dual-imagery processing model"to explain how the haptic system establishes mapping between 2D planes and 3D space during haptic 2D image recognition. In this model, information acquired through touch forms object imagery (concerning object size, shape, and texture) and spatial imagery (concerning spatial relationships, perspective, and viewpoint). Successful haptic recognition depends on effective integration of these two imagery systems, requiring successful matching between object and spatial imagery to establish mapping between 2D images and 3D object representations, thereby accessing 3D object representations in long-term memory. Finally, we summarize critical unresolved questions and future research directions.

1 Visual Factors Affecting Haptic 2D-to-3D Spatial Information Transformation

Previous research on factors affecting haptic recognition of 2D images can be broadly categorized into two types: first, 2D image features such as texture (Nguyen et al., 2018; Thompson et al., 2006; Theurel et al., 2013), perspective (Gong et al., 2020; Lebaz et al., 2012; Lederman et al., 1990; Gong et al., 2018), viewpoint (Heller et al., 2002), and image complexity (Yu et al., 2017); second, individual factors of the touch explorer, where lack of haptic experience, low familiarity with images, and absence of visual experience in blind individuals all hinder haptic recognition (Lederman et al., 1990; Mazella et al., 2018; Overvliet & Krampe, 2018). Since current tactile 2D images are generated based on visual principles, following planar visual display principles and characteristics that may not be suitable for haptic perception, this paper focuses on visual factors affecting haptic 2D-to-3D spatial information transformation.

The primary visual factors affecting haptic perception are monocular depth cues used on 2D planes to express 3D depth and stereoscopic information, mainly including perspective, viewpoint, occlusion, texture gradient, and hollow-out (Lebreton, 2016). When presenting 3D objects and scenes on 2D planes, existing methods almost exclusively rely on these visual principles to express depth and stereoscopic information. Although objects project as 2D images on the retina, the visual system can rapidly acquire depth information and 3D features through binocular disparity, monocular cues, and extensive perceptual learning with eye-hand coordination (Zhang & Li, 2020; Wang et al., 2020). However, people lack experience in converting depth information from 2D planes to 3D space through touch (Klatzky & Lederman, 2011), making it difficult to obtain depth information expressed in 2D images (Heller et al., 2006; Nguyen et al., 2018).

Figure 1. Illustrations of visual monocular cues

As shown in Figure 1a, perspective uses the visual principle of lines and surfaces converging on a 2D plane to represent 3D objects and space. It is the most important monocular cue, closely related to viewpoint, providing a 3D view of objects. For the same 3D object, different viewpoints produce different 2D images, and changes in apparent object rotation angle inevitably involve changes in perspective relationships (Heller et al., 2006). Figure 1b shows three viewpoints in a 2D line drawing of a hexagonal prism: top view, 3D view, and front view. The top and front views cannot display the hexagonal prism' s 3D spatial information, whereas the 3D view using perspective relationships can express its 3D spatial information. Besides perspective, hollow-out, occlusion, and texture gradient are also monocular cues for depth information (see Figure 1). In 3D objects, hollow-out refers to removing interior portions to create empty space. When hollow-out 3D objects become 2D line drawings (Figure 1c), understanding hollow-out information through touch is difficult. Occlusion (also called overlap) provides information about spatial position (front/back, near/far), requiring perceptual completion of occluded portions (Lebreton, 2016). Occlusion cues in 2D images are modality-specific spatial representation methods for vision, but distinguishing near/far relationships between overlapping parts and completing occluded portions is difficult through touch alone. For example, in Figure 1d showing cherries, visual perception easily understands three overlapping cherries, but haptic touch tends to perceive them as a single object. Texture gradient refers to surface texture becoming sparser near the observer and denser at a distance (Figure 1e).

Among these visual factors, viewpoint and perspective have received relatively more attention in haptic research, while occlusion, hollow-out, and texture gradient have been less studied. Only a few studies have examined texture gradient effects on haptic 2D image recognition, finding that appropriate textures can facilitate recognition performance (Nguyen et al., 2018; Thompson et al., 2006; Theurel et al., 2013). For instance, using texture information to express depth information in images benefits haptic recognition. Applying different textures to different surfaces of objects in 2D images can provide spatial information for haptic perception (Thompson et al., 2006). Creating 2D images with raised object contours plus detailed textures yields higher haptic recognition performance than line drawings alone or shape outlines without textures (Theurel et al., 2013). Varying line thickness according to distance from the observer—thicker lines for nearer parts—can also enhance depth information and improve haptic recognition performance (Nguyen et al., 2018). While perspective, viewpoint, occlusion, texture gradient, and hollow-out provide depth information in visual 2D images, these cues may interfere with haptic recognition unless specially processed as described above (Gong et al., 2020).

Haptic recognition of 2D images involves constructing a 3D mental representation from haptically perceived 2D images and matching it with stored 3D object concept representations. In contrast, haptic recognition of 3D objects lacks this 2D-to-3D mapping and construction process. Therefore, examining viewpoint effects on haptic 3D object recognition may illuminate the role of viewpoint and perspective in haptic 2D image recognition. Below, we first discuss viewpoint effects on haptic recognition of 3D objects.

1.1 Viewpoint Effects on Haptic Recognition of 3D Objects

Visual perception exhibits object constancy (Qian & Petrov, 2016), where viewpoint-dependent and viewpoint-independent information are simultaneously encoded (Tarr & Hayward, 2017). Haptic modality also shows object constancy. When recognizing 3D objects haptically, people must integrate multiple tactile viewpoints—tactile information from different hands and fingers—to form object representations for localization, identification, and manipulation (Heed et al., 2015; Yau et al., 2016). These hand exploration angles are referred to as "viewpoints" in previous research. Since both hands can simultaneously touch objects from different angles, haptic recognition of 3D objects might intuitively be viewpoint-independent. However, studies have found viewpoint preferences in sighted individuals when haptically recognizing artificial geometric objects. When the front-facing surface of an object was covered, allowing only exploration of the back-facing surface, recognition performance was better than in the front-view condition (where the back was covered) (Newell et al., 2001). Even when allowing more comprehensive haptic exploration of multiple surfaces, haptic recognition remained susceptible to viewpoint interference when matching objects rotated in viewpoint (Lacey et al., 2007). Researchers suggest this may be due to the common exploration pattern of keeping the thumb stationary while moving other fingers, biasing tactile exploration toward the back-facing "viewpoint" (Lacey et al., 2007).

Both studies used artificial geometric objects, and viewpoint effects might result from unfamiliarity with such objects (Woods et al., 2008). Therefore, one study compared haptic recognition of familiar 3D objects (e.g., toy horses, toy houses) with artificial geometric objects. For unfamiliar 3D objects, both blindfolded sighted individuals showed viewpoint-dependent recognition in both haptic and visual modalities. For familiar 3D objects, blindfolded sighted individuals showed viewpoint-independent haptic recognition (Woods et al., 2008). With haptic training on unfamiliar 3D geometric objects, blindfolded sighted individuals could achieve viewpoint-independent recognition (Lacey et al., 2009).

In contrast to viewpoint-dependent recognition in blindfolded sighted individuals, early blind individuals (EB, blind before age three) show viewpoint-independent haptic recognition of artificial geometric objects (Occelli et al., 2016). Thus, haptic 3D object recognition in blindfolded sighted individuals depends on object familiarity, whereas recognition in visually impaired individuals is viewpoint-independent regardless of familiarity. This difference may arise because visually impaired individuals lack visual experience, leading them to focus more on spatial relationships between object parts during tactile processing (Occelli et al., 2016), and possibly because their richer tactile experience enables more effective acquisition of spatial relationship information. For instance, Withagen et al. (2013) found that adult visually impaired individuals employed more mature haptic exploration strategies than visually impaired children, yielding better recognition performance. Blindfolded sighted individuals, however, may be less effective at acquiring spatial relationship information through touch, relying more on object feature recognition, making them more susceptible to viewpoint interference for unfamiliar 3D objects.

1.2 Perspective and Viewpoint Effects on Haptic Recognition of 2D Images

Perspective information in 2D images provides height, width, depth, and viewpoint information about 3D objects. Changes in object viewpoint affect perspective expression. Current research on perspective and viewpoint effects on haptic 2D image recognition has revealed four main findings.

First, 3D views created by perspective relationships interfere with haptic recognition of 2D images. When haptically recognizing 2D line drawings of natural objects, blindfolded sighted individuals show lower recognition performance for drawings containing perspective information compared to those without perspective (Gong et al., 2020; Lebaz et al., 2012; Lederman et al., 1990; Gong et al., 2018). This indicates that perspective relationships in natural object drawings interfere with haptic recognition. Strong perspective images containing multiple surface views may enhance visual depth understanding but increase complexity for haptic 2D images, creating recognition obstacles. Consistent with these findings, practical experience suggests that perspective is difficult to recognize haptically. The Braille Authority of North America (2010) guidelines state that visually impaired individuals lack visual experience to understand perspective cues and recommend removing perspective from tactile images unless explicitly required.

Second, viewpoint preferences exist when haptically recognizing 2D images of 3D objects. When selecting from four 2D images the one matching a target 3D geometric object, both blindfolded sighted individuals (Heller et al., 2002) and blind participants (Heller et al., 2006) showed best performance for top views. When identifying specified viewpoints among four 2D house images, both low-vision and blind participants performed best with top-view 2D images (Heller et al., 2009). These studies demonstrate that haptic recognition of 2D images is viewpoint-dependent. The top-view advantage may occur because the 3D objects used (cylindrical geometries, houses) provided maximal spatial relationship and object feature information from top views (e.g., distinctive tops, roofs). However, viewpoint advantage effects depend on stimulus type and task difficulty. When 3D objects changed from simple to complex geometries, the top-view advantage disappeared for blind, low-vision, and blindfolded sighted participants (Heller et al., 2009; Heller et al., 2006). Heller' s studies are limited by object types and cannot definitively establish top view as optimal for all categories. Research on common daily objects (e.g., apples, pants, scissors) found symmetry-plane advantages for axisymmetric objects (Gong et al., 2020; Sinha & Kalia, 2012; Gong et al., 2018). Symmetric objects like butterflies and pants are easier to recognize when presented in their symmetry plane than non-symmetric objects. Future research should investigate viewpoint preferences across different object categories.

Third, perspective can sometimes facilitate haptic recognition of 2D images under specific conditions. When blindfolded sighted participants selected from four 2D images the one matching a target 2D image, performance was better when the target had a perspective-rich 3D view versus a non-perspective 3D view. However, this advantage disappeared when the four alternatives contained perspective (Heller et al., 2006). When selecting from four 2D images the one matching a complex 3D geometric object, early blind participants also showed best performance for perspective-containing 2D images (Heller et al., 2009). This indicates that both blindfolded sighted and blind individuals can understand spatial relationships between object parts provided by perspective (Heller et al., 2009; Heller et al., 2006). The advantage for perspective-rich targets may occur because perspective provides more spatial information for better matching with alternative 2D images. When the target is a 3D object, the object itself provides sufficient spatial information, so perspective in alternatives can also facilitate recognition.

Fourth, visually impaired individuals without visual experience can learn to understand depth information in perspective cues through training. When matching a 3D angle formed by two boards with multiple 2D angle drawings from different viewpoints, sighted, congenitally blind, and late blind participants showed no significant performance differences. When asked to draw the touched board angle, congenitally blind participants produced 2D drawings conforming to 3D perspective rules (Heller et al., 2002). A case study found that guided practice enabled a blind individual to learn perspective rules and draw 2D images of 3D objects from different angles with proper perspective (Kennedy & Juricevic, 2016).

These studies demonstrate viewpoint preferences in haptic 2D image recognition, with preferences varying across object categories. Although understanding perspective haptically is challenging, it is not impossible. Researchers have attempted to create local cues in tactile 2D images to indicate perspective and viewpoint information. As mentioned earlier, using different textures for different viewpoint surfaces provides spatial information and improves recognition performance (Thompson et al., 2006). Varying line thickness according to distance—thicker lines for nearer parts—enables blindfolded sighted individuals to effectively recognize perspective and depth information, significantly improving haptic recognition performance (Nguyen et al., 2018). Thus, further research on visual factors affecting haptic 2D image recognition will help improve tactile image design and enhance recognition performance.

2 Neural Basis of Haptic 2D-to-3D Spatial Information Transformation

Haptic recognition of 2D images, like haptic recognition of 3D objects, fundamentally depends on tactile perception of line or surface orientation and curvature, as well as texture information. Current neural mechanism research on haptics has focused primarily on 2D and 3D shape and texture perception, but the neural basis for how haptics recognizes 3D objects and space from 2D images remains understudied.

The foundation for perceiving line/surface orientation, curvature, and texture lies in various mechanoreceptors located in superficial skin layers, muscles, tendons, joints, and ligaments. These receptors respond to skin deformation and limb movement, generating tactile and proprioceptive sensations that travel via the medial lemniscal pathway to the thalamus and ultimately to somatosensory cortices, including primary somatosensory cortex (S1) in Brodmann areas 1, 2, 3a, and 3b, and secondary somatosensory cortex (S2) (Delhaye et al., 2018; Yau et al., 2016). These areas encode tactile stimulus roughness, orientation, curvature, and shape (Kitada, 2016; Yau et al., 2016). Damage to area 3b impairs texture recognition and shape discrimination, while area 2 damage prevents tactile perception of shape and size changes (Delhaye et al., 2018).

Extensive research has found overlapping or similar patterns in the neural basis for object representation between haptic and visual modalities (Kitada, 2016; Lacey & Sathian, 2014; Sathian, 2016; Yau et al., 2016), indicating that neural networks activated during tactile information encoding are not modality-specific but associated with multiple sensory modalities. Since current tactile 2D images are almost exclusively generated based on visual principles, haptic recognition of 2D images may rely more heavily on visual system participation and visuo-haptic information integration. Therefore, overlapping neural substrates and visuo-haptic crossmodal integration mechanisms can inform research on the neural mechanisms of haptic 2D image recognition.

2.1 Overlapping Neural Basis of Haptic and Visual Processing

First, haptic and visual modalities show substantial neural overlap when processing shape, size, and texture information. Both modalities involve the intraparietal sulcus (IPS) and lateral occipital complex (LOC) in object shape recognition (Sathian, 2016). LOC is crucial for shape processing in both vision and haptics: it activates during visual presentation of 2D images and 3D objects (e.g., tools, animals, toys) (Amedi et al., 2002) and during haptic exploration of 3D objects (Hernandez-Perez et al., 2017), 2D letter images (Stoesz et al., 2003), and simple 2D shapes (e.g., hooks) (Prather et al., 2004). Tactile detection of object size changes activates IPS and lateral frontal cortex, showing similar activation patterns in vision (Perini et al., 2020). Tactile judgments of texture and roughness also involve visual cortex: tactile perception of raised-dot roughness activates operculo-insular cortex and ventral temporal cortex (VTC), while tactile perception of raised-dot spatial density activates primary somatosensory cortex and visual cortex (Eck et al., 2016).

Second, visual cortex participates in haptic 2D image generation and tactile imagery formation. When congenitally blind individuals without any visual experience draw 2D images using an electronic stylus, primary visual cortex V1 shows significant activation (Likova, 2012). When blindfolded sighted and congenitally blind individuals generate mental images of previously touched objects, S1 activates, consistent with regions activated in visual mental imagery tasks (de Borst & de Gelder, 2016; de Borst & de Gelder, 2019).

Third, tactile working memory activates the same brain regions as visual working memory. When measuring tactile working memory through exploration of angles formed by three raised lines, the inferior frontal gyrus (IFG), posterior parietal cortex (PPC), and medial frontal gyri (mFG) show significant activation (Yang et al., 2014). IFG and mFG also participate in tactile texture working memory processing (Kaas et al., 2013), and all these regions are involved in visual working memory (Yang et al., 2014). Further research indicates that selective attention in visual and tactile working memory may be regulated by shared supramodal control processes (Katus & Eimer, 2020a), while spatial attention shifts may be controlled by modality-specific mechanisms (Katus & Eimer, 2020b).

Finally, when 2D image processing becomes familiarized, similar neural activation patterns emerge in both haptic and visual modalities. The perirhinal cortex (PRC) is crucial for multimodal information integration and participates in visuo-haptic integration (Cacciamani & Likova, 2016; Holdstock et al., 2009). During visual "old-new" judgment tasks using images and faces, PRC activation decreases for "old" stimuli (Henson et al., 2003); similar activation reduction patterns in PRC are observed when tactile familiarity with 2D images changes (Cacciamani & Likova, 2016).

These studies suggest substantial neural overlap between haptic and visual processing of 2D images (Desmarais et al., 2017; Lacey & Sathian, 2014; Sathian, 2016). This overlapping neural basis may indicate shared representational systems or that these regions constitute fundamental crossmodal perceptual brain areas (Cacciamani & Likova, 2016). Therefore, the neural mechanisms of haptic 2D image recognition require further investigation.

2.2 Neural Basis of Visuo-Haptic Integration

Despite overlapping neural substrates, haptic and visual modalities differ in perceptual properties and efficiency, necessitating information integration to avoid misjudgment in complex environments (Toprak et al., 2018). When the cognitive system integrates information from both modalities, perceptual precision increases compared to haptic information alone (Ernst & Banks, 2002; Toprak et al., 2018; Wan et al., 2020), and hand exploration speed also increases (Camponogara & Volcic, 2019).

Cortical regions in ventral and dorsal pathways, previously considered vision-specific, have been found to participate in haptic tasks (Freud et al., 2017; Lacey & Sathian, 2014; Sathian, 2016). As mentioned earlier, LOC participates in both visual and haptic object recognition. The specific LOC region involved in visual and object recognition is called the lateral occipital tactile-visual region (LOtv), considered an integration site for vision and haptics (Lacey & Sathian, 2014).

The adult brain integrates visuo-haptic object information in a statistically optimal manner, weighting each sensory channel according to its reliability (Ernst

& Banks, 2002). The neural mechanisms underlying how object perception integrates visual and haptic information into more abstract, meaningful perceptual information for learning and recognition remain incompletely understood. However, many studies indicate that this integration ability is not innate but gradually develops through maturation. Before age 8, visuo-haptic spatial information integration is far from optimal; only by ages 8-10 does children' s visuo-haptic integration develop to adult levels (Gori et al., 2008). Although congenitally blind or visually impaired individuals experience years of visual deprivation without developing multisensory integration, their visuo-haptic integration ability can reach adult optimal levels within months after vision restoration surgery (Senna et al., 2021). This suggests that early exposure to multisensory signals is not essential for developing multisensory integration, which can be acquired through postnatal learning even after prolonged visual deprivation.

3 Theoretical Models of Haptic 2D-to-3D Spatial Information Transformation

Haptic recognition of 2D images requires constructing 3D object and spatial information from perceived 2D planar information and matching it with stored 3D object representations. Therefore, constructing 3D objects and space from 2D planar information is crucial for haptic 2D image recognition. Additionally, haptic recognition is constrained by limited sensory channel capacity, preventing holistic processing and instead relying on sequential processing according to exploration order (Loomis et al., 1991). During exploration, touchers must temporarily store explored information (line orientation and curvature, size, texture, etc.) in working memory for integration with subsequently explored information, gradually forming complete object representations (Yoshida et al., 2015). Thus, haptic recognition relies more heavily on working memory for real-time object representation updates, requiring greater working memory resources (Lacey & Sathian, 2014). For sighted individuals, haptically formed object representations are similar to visual imagery (Overvliet et al., 2013). When tactile 2D images contain visual factors like perspective and viewpoint, visual imagery becomes particularly important. Klatzky and Lederman (1988) first recognized the important role of imagery in haptic 2D image recognition and proposed the "image-mediation model" to explain its cognitive mechanisms.

3.1 Image-Mediation Model

The image-mediation model posits that haptic recognition of 2D images involves perceiving lines and junctions through tactile receptors, performing a visual transformation in the brain to form visual imagery, then comparing this visual imagery with stored knowledge representations to complete recognition (Overvliet et al., 2013).

Figure 2. Image-mediation model (adapted from Lederman et al., 1990)

The image-mediation model (Figure 2) has received some empirical support. For example, congenitally blind individuals without visual experience show lower 2D image recognition performance than visually experienced blindfolded sighted individuals (Lederman et al., 1990), and blindfolded sighted individuals with high visual imagery ability outperform those with low ability (Lebaz et al., 2012). However, other studies found no significant performance differences between blindfolded sighted and blind individuals in haptic 2D image recognition (Heller et al., 2009; Lebaz et al., 2012; Picard et al., 2010), contradicting the model' s "visual transformation" and "visual imagery" mechanisms. Since congenitally blind individuals have minimal visual experience, if visual transformation were necessary for haptic 2D image recognition, blindfolded sighted individuals should outperform blind individuals.

3.2 Object Imagery and Spatial Imagery

Although congenitally blind individuals lack visual experience and may not form visual imagery like sighted individuals, this does not mean they cannot form imagery. Recent imagery research has distinguished two subsystems: object imagery and spatial imagery. Object imagery involves perceptual features including shape, texture, color, and brightness, while spatial imagery involves spatial location, object components, and spatial relationships and transformations between parts (Blajenkova et al., 2006; Höffler et al., 2017; Pearson, 2019; Roldan, 2017; Sheldon et al., 2017). Individuals differ in their preferences for object versus spatial imagery when forming mental images (Lacey et al., 2011), which can be assessed using the Object-Spatial Imagery Questionnaire (OSIQ; Blajenkova et al., 2006). The haptic system also contains similar object imagery and spatial imagery subsystems, and individual preferences for these imagery types affect integration of haptic information for 3D object recognition (Lacey et al., 2011). As mentioned earlier, blindfolded sighted individuals show viewpoint-dependent recognition of 3D objects, whereas blind individuals show viewpoint-independent recognition (Occelli et al., 2016). We propose this occurs because blind individuals lack visual experience and may have difficulty forming object imagery but possess rich tactile experience enabling accurate spatial imagery formation, making them more reliant on spatial imagery for haptic 2D image recognition. Sighted individuals, with rich visual experience, have developed accurate and rich object imagery for familiar objects, making them more reliant on object imagery during haptic 2D image recognition and thus more susceptible to viewpoint changes.

Based on this analysis, we propose that haptic 2D image recognition involves two distinct imagery processing modules: object imagery and spatial imagery. While the image-mediation model may explain some mechanisms, it does not consider processing characteristics of the two imagery types or how individual imagery preferences affect haptic recognition. Building on previous research, we propose a dual-imagery processing model that distinguishes object imagery and spatial imagery modules to expand and enrich theoretical perspectives on haptic 2D image recognition.

3.3 Dual-Imagery Processing Model

We propose the dual-imagery processing model for haptic 2D image recognition (Figure 3). This model includes two imagery processing modules: one based on object imagery (concerning object texture, shape, and size) and another based on spatial imagery (concerning spatial relationships, perspective, and viewpoint). Successful haptic 2D image recognition depends on effective information integration from both imagery systems.

The model' s main claims include three points:

First, the "haptic perception"module receives tactile and proprioceptive information from mechanoreceptors in skin, muscles, tendons, and ligaments, acquiring object texture, shape, and size information. Through further sensory integration, it also acquires spatial relationship information between object parts and perspective/viewpoint information. Although spatial imagery requires further sensory integration to acquire spatial relationship information, this does not necessarily mean spatial imagery formation lags behind object imagery. The sequence depends on the current cognitive task, with limited cognitive resources dynamically allocated between the two imagery types.

Second, the "working memory" module receives object information (texture, shape, size) from haptic perception to primarily form object imagery of 2D images, constituting the object imagery-based processing submodule. It also receives spatial information (spatial relationships, perspective, viewpoint) to primarily form spatial imagery of 2D images, constituting the spatial imagery-based processing submodule.

Third, successful haptic 2D image recognition depends on joint operation of both object imagery and spatial imagery processing submodules. The "long-term memory" module stores individual knowledge and object representations, with dynamic, bidirectional information transfer between modules. Successful integration of the two imagery systems requires matching object and spatial imagery based on mapping between 2D images and 3D space. Effective integration facilitates access to object representations in long-term memory, whereas ineffective integration may prevent recognition. Extensive learning and training in haptic 2D image recognition may enhance recognition ability.

Although the dual-imagery processing model requires further experimental validation, current research findings on haptic 2D image recognition in blindfolded sighted and visually impaired individuals can serve as supporting evidence, and the model can provide preliminary explanations for these results.

First, the dual-imagery processing model can explain why 2D images containing perspective are more difficult to recognize haptically. As discussed, 2D images with perspective-rich 3D views typically reduce haptic recognition performance (Gong et al., 2020; Lebaz et al., 2012; Lederman et al., 1990; Gong et al., 2018).

According to the model, perspective-rich 3D views necessarily distort side shapes of 3D objects projected onto 2D planes. Although haptics can acquire spatial relationships between lines, this may lead to spatial imagery inconsistent with the actual 3D object shape, preventing correct object imagery construction and successful matching with long-term memory representations, thereby increasing recognition difficulty.

Second, the model can explain viewpoint preferences observed in 2D image matching. The viewpoint preferences discussed earlier (Gong et al., 2020; Heller et al., 2006; Heller et al., 2009; Sinha & Kalia, 2012; Gong et al., 2018) may occur because certain viewpoints produce better integration between object imagery and spatial imagery during exploration, making those viewpoints easier to recognize. For symmetric objects like butterflies and pants, symmetry-plane presentation yields more consistent object and spatial imagery, facilitating integration.

Finally, the model can resolve controversies about visual experience. Previous studies have debated the role of visual experience in haptic 2D image recognition, with some finding worse performance in blind than sighted individuals (Cornoldi et al., 2009; Gong et al., 2020; Lederman et al., 1990) and others finding no differences (Heller et al., 2009; Lebaz et al., 2012; Picard et al., 2010). According to the dual-imagery processing model, visual experience may not directly affect haptic recognition performance but may influence individual imagery ability and preferences, thereby causing performance differences. One study found significant performance differences among blindfolded sighted, early blind, and late blind participants in haptic memory and recognition of 2D images, with performance positively correlating with imagery ability (Picard et al., 2010). Another study found no performance differences between blindfolded sighted and congenitally blind participants when recognizing final dot positions in haptically memorized routes, but sighted participants performed better when recognizing entire routes (Cornoldi et al., 2009). This may occur because sighted individuals tend to use object imagery to memorize whole routes, while congenitally blind individuals prefer spatial imagery to memorize relative positions of each part, leading to performance differences in whole-route recognition.

4 Summary and Outlook

This paper has summarized and analyzed major visual factors affecting haptic 2D image recognition, examined their underlying neural mechanisms, and proposed a dual-imagery processing model to explain the cognitive mechanisms of haptic 2D image recognition. Research on haptic 2D image recognition is burgeoning, with numerous scientific questions and application challenges remaining to be addressed.

First, the proposed dual-imagery processing model requires systematic experimental validation. According to the model, performance differences between visually impaired and sighted individuals in haptic 2D image recognition (and possibly haptic 3D object recognition) may stem from different imagery type preferences formed during haptic exploration. Future research should examine whether visually impaired and sighted individuals show different preferences for object versus spatial imagery. Studies on sighted individuals indicate that visual imagery preferences affect object representation integration (Sathian et al., 2011). Whether differences exist among congenitally blind, early blind, and late blind individuals, and between blind and sighted groups, remains unclear. Additionally, most current research measures haptic imagery ability through self-report questionnaires (Pearson, 2019), which may be unreliable. Vividness of visual imagery is not a fixed trait but may change dynamically, measurable through brain imaging of the entire brain network including sensory-perceptual systems and their overlap (Bergmann et al., 2016; Dijkstra et al., 2017; Pearson, 2019). Given the overlapping neural patterns for visual and haptic object imagery and object properties (Desmarais et al., 2017; Lacey & Sathian, 2014; Sathian, 2016), brain imaging can also measure vividness of haptic imagery.

Second, future research should explore how the dual-imagery processing model can guide design of tactile aids and haptic guidance for 2D images. With advances in electronic tactile display technology, tactile 2D image design urgently needs guidance from cognitive mechanism research. The dual-imagery processing model separates haptic 2D image recognition into object imagery and spatial imagery modules, suggesting that practical applications could design specifically for each module. For example, highlighting diagnostic shape structures (e.g., typical viewpoint shapes, symmetric structures) could facilitate object representation modules, while using lines of varying thickness and density to cue perspective, viewpoint, occlusion, or hollow-out information could enhance spatial imagery module processing. Future research should conduct validation and application studies based on this model to propose actionable design principles and haptic guidance strategies. Application research may also inform cognitive mechanism studies of haptic 2D image recognition.

Third, whether visually impaired individuals' lack of visual experience can be compensated through extensive haptic learning to better understand perspective and viewpoint relationships and establish mapping between 2D images and 3D objects requires further investigation. Previous studies show that haptic learning and training facilitate recognition of both 2D images (Vinter et al., 2018; Vinter et al., 2020) and 3D objects (Lacey et al., 2009). Future research should examine whether haptic learning can establish mapping between 2D perspective images and 3D objects from different viewpoints to ultimately achieve viewpoint-independent haptic recognition, and whether haptic learning can link perspective in 2D images with viewpoints in 3D objects to eliminate perspective interference.

Finally, developmental psychology issues warrant attention. Studies show that practice enhances children's haptic 2D image recognition ability (Overvliet & Krampe, 2018; Vinter et al., 2018; Vinter et al., 2020), and haptic 2D image recognition improves with age (Mazella et al., 2018; Withagen et al., 2013).

However, the causes of age-related differences remain unclear. These differences may result from more mature haptic exploration strategies in adults (Withagen et al., 2013), differences in spatial reference frames and working memory capacity between children and adults (Overvliet & Krampe, 2018), or age-related improvements in haptic shape recognition ability (Mazella et al., 2018). Developmental research on haptic 2D image recognition will further our understanding of haptic perception mechanisms and provide theoretical guidance for training haptic abilities in visually impaired children.

References

Gong, J., Yu, W., Qu, T., Liu, Y., Fu, X., & Xu, Y. (2018). Quantitative analysis of factors affecting tactile image recognition. *Journal of Computer-Aided Design & Computer Graphics*, 30(08), 1438–1445. doi: 10.3724/SP.J.1089.2018.16799

Jiao, Y., Gong, J., & Xu, Y. (2016). Design research on the Graile tactile graphics display for blind individuals. *Zhuangshi*, No.273(01), 96–98. doi:CNKI:SUN:ZSHI.0.2016-01-031

Lu, C., & Zong, X. (2017). Research on design methods for tactile graphic displays for blind individuals. *Design*, 000(007), 126–127. doi:10.3969/j.issn.1003-

Wang, G., Xi, J., Chen, N., & Huang, C. (2020). Neural mechanisms of binocular disparity and perceptual learning effects. *Advances in Psychological Science*, 1–14. doi:10.3724/SP.J.1042.2021.00056

Yu, W., Liu, Y., Fu, X., Gong, J., & Xu, Y. (2019). Cognitive mechanisms of tactile 2D image recognition. *Advances in Psychological Science*, 27(4), 611–622. doi:10.3724/sp.J.1042.2019.00611

Amedi, A., Jacobson, G., Hendler, T., Malach, R., & Zohary, E. (2002). Convergence of visual and tactile shape processing in the human lateral occipital complex. *Cerebral Cortex*, 12(11), 1202–1212. doi:10.1093/cercor/12.11.1202

Braille Authority of North America. (2010). *Guidelines and standards for tactile graphics*. Retrieved from http://www.brailleauthority.org/tg/web-manual/index.html

Bara, F., Gentaz, E., & Valente, D. (2018). The effect of tactile illustrations on comprehension of storybooks by three children with visual impairments: An exploratory study. *Journal of Visual Impairment & Blindness*, 112(6), 759–765. doi:10.1177/0145482X1811200610

Bauer, C., Yazzolino, L., Hirsch, G., Cattaneo, Z., Vecchi, T., & Merabet, L. B. (2015). Neural correlates associated with superior tactile symmetry perception in the early blind. *Cortex*, 63, 104–117. doi:10.1016/j.cortex.2014.08.003

Bergmann, J., Genç, E., Kohler, A., Singer, W., & Pearson, J. (2016). Smaller primary visual cortex is associated with stronger, but less precise mental imagery.

Cerebral Cortex, 26(9), 3838-3850. doi:10.1093/cercor/bhv186

Blajenkova, O., Kozhevnikov, M., & Motes, M. A. (2006). Object-spatial imagery: A new self-report imagery questionnaire. *Applied Cognitive Psychology*, 20(2), 239–263. doi:10.1002/acp.1182

Cacciamani, L., & Likova, L. T. (2016). Tactile object familiarity in the blind brain reveals the supramodal perceptual-mnemonic nature of the perirhinal cortex. *Frontiers in Human Neuroscience*, 10, 92. doi:10.3389/fnhum.2016.00092

Camponogara, I., & Volcic, R. (2019). Grasping adjustments to haptic, visual, and visuo-haptic object perturbations are contingent on the sensory modality. *Journal of Neurophysiology*, 122(6), 2614–2620. doi:10.1152/jn.00452.2019

Cavazos Quero, L., Bartolomé, J. I., & Cho, J. (2021). Accessible visual artworks for blind and visually impaired people: Comparing a multimodal approach with tactile graphics. *Electronics*, 10(3), 297. doi: 10.3390/electronics10030297

Cornoldi, C., Tinti, C., Mammarella, I. C., Re, A. M., & Varotto, D. (2009). Memory for an imagined pathway and strategy effects in sighted and in totally congenitally blind individuals. *Acta Psychologica*, 130(1), 11–16. doi:10.1016/j.actpsy.2008.09.012

de Borst, A. W., & de Gelder, B. (2016). fMRI-based multivariate pattern analyses reveal imagery modality and imagery content specific representations in primary somatosensory, motor and auditory cortices. *Cerebral Cortex*, 27(8), 3994–4009. doi:10.1093/cercor/bhw211

de Borst, A. W., & de Gelder, B. (2019). Mental imagery follows similar cortical reorganization as perception: Intramodal and cross-modal plasticity in congenitally blind. *Cerebral Cortex*, 29(7), 2859–2875. doi:10.1093/cercor/bhy151

Delhaye, B. P., Long, K. H., & Bensmaia, S. J. (2018). Neural basis of touch and proprioception in primate cortex. *Comprehensive Physiology*, 8(4), 1575-1602. doi:10.1002/cphy.c170033

Desmarais, G., Meade, M., Wells, T., & Nadeau, M. (2017). Visuo-haptic integration in object identification using novel objects. *Attention, Perception and Psychophysics*, 79(8), 2478–2498. doi:10.3758/s13414-017-1382-x

Dijkstra, N., Bosch, S. E., & Gerven, M. A. J. v. (2017). Vividness of visual imagery depends on the neural overlap with perception in visual areas. *The Journal of Neuroscience*, 37(5), 1367–1373. doi:10.1523/JNEUROSCI.3022-16.2016

Eck, J., Kaas, A. L., Mulders, J. L., Hausfeld, L., Kourtzi, Z., & Goebel, R. (2016). The effect of task instruction on haptic texture processing: The neural underpinning of roughness and spatial density perception. *Cerebral Cortex*, 26(1), 384–401. doi:10.1093/cercor/bhu294

Ernst, M. O., & Banks, M. S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, 415(6870), 429–433.

doi:10.1038/415429a

Flaxman, S. R., Bourne, R. R. A., Resnikoff, S., Ackland, P., Braithwaite, T., Cicinelli, M. V., . . . Varma, R. (2017). Global causes of blindness and distance vision impairment 1990–2020: A systematic review and meta-analysis. *The Lancet Global Health*, 5(12), 1221–1234. doi:10.1016/s2214-109x(17)30393-5

Freud, E., Culham, J. C., Plaut, D. C., & Behrmann, M. (2017). The large-scale organization of shape processing in the ventral and dorsal pathways. *Elife*, 6, 27576. doi:10.7554/eLife.27576

Garcia, G. G., Grau, R. R., Aldrich, F. K., & Cheng, P. C. (2020). Multi-touch interaction data analysis system (MIDAS) for 2-D tactile display research. *Behavior Research Methods*, 52(2), 813–837. doi:10.3758/s13428-

Gong, J., Yu, W., Ni, L., Jiao, Y., Liu, Y., Fu, X., & Xu, Y. (2020, October). "I can' t name it, but I can perceive it" : Conceptual and operational design of "tactile accuracy" assisting tactile image cognition. Paper presented at the 22nd International ACM SIGACCESS Conference on Computers and Accessibility, Virtual Event, Greece. doi: 10.1145/3373625.3417015

Gori, M., Del Viva, M., Sandini, G., & Burr, D. C. (2008). Young children do not integrate visual and haptic form information. *Current Biology*, 18(9), 694–698. doi:10.1016/j.cub.2008.04.036

Heed, T., Buchholz, V. N., Engel, A. K., & Röder, B. (2015). Tactile remapping: From coordinate transformation to integration in sensorimotor processing. *Trends in Cognitive Sciences*, 19(5), 251–258. doi:10.1016/j.tics.2015.03.001

Heller, M., Riddle, T., Fulkerson, E., Wemple, L., Walk, A., Guthrie, S., . . . Klaus, P. (2009). The influence of viewpoint and object detail in blind people when matching pictures to complex objects. *Perception*, 38, 1234–1250. doi:10.1068/p5596

Heller, M. A., Brackett, D. D., Scroggs, E., Steffen, H., Heatherly, K., & Salik, S. (2002). Tangible pictures: Viewpoint effects and linear perspective in visually impaired people. *Perception*, 31(6), 747-769. doi:10.1068/p3253

Heller, M. A., Kennedy, J. M., Clark, A., McCarthy, M., Borgert, A., Wemple, L., . . . Riddle, T. (2006). Viewpoint and orientation influence picture recognition in the blind. *Perception*, 35(10), 1397–1420. doi:10.1068/p5460

Henson, R. N. A., Cansino, S., Herron, J. E., Robb, W. G. K., & Rugg, M. D. (2003). A familiarity signal in human anterior medial temporal cortex? *Hippocampus*, 13(2), 301-304. doi:10.1002/hipo.10117

Hernandez-Perez, R., Cuaya, L. V., Rojas-Hortelano, E., Reyes-Aguilar, A., Concha, L., & de Lafuente, V. (2017). Tactile object categories can be decoded from the parietal and lateral-occipital cortices. *Neuroscience*, 352, 226–235. doi:10.1016/j.neuroscience.2017.03.038

Höffler, T. N., Koć-Januchta, M., & Leutner, D. (2017). More evidence for three types of cognitive style: Validating the object-spatial imagery and verbal questionnaire using eye tracking when learning with texts and pictures. *Applied Cognitive Psychology*, 31(1), 109–115. doi:10.1002/acp.3300

Holdstock, J. S., Hocking, J., Notley, P., Devlin, J. T., & Price, C. J. (2009). Integrating visual and tactile information in the perirhinal cortex. *Cerebral Cortex*, 19(12), 2993–3000. doi:10.1093/cercor/bhp073

Kaas, A. L., van Mier, H., Visser, M., & Goebel, R. (2013). The neural substrate for working memory of tactile surface texture. *Human Brain Mapping*, 34(5), 1148–1162. doi:10.1002/hbm.21500

Katus, T., & Eimer, M. (2020a). Retrospective selection in visual and tactile working memory is mediated by shared control mechanisms. *Journal of Cognitive Neuroscience*, 32(3), 546–557. doi:10.1162/jocn_a_01492

Katus, T., & Eimer, M. (2020b). Shifts of spatial attention in visual and tactile working memory are controlled by independent modality-specific mechanisms. *Cerebral Cortex*, 30(1), 296–310. doi:10.1093/cercor/bhz088

Kennedy, J. M., & Juricevic, I. (2016). Foreshortening, convergence and drawings from a blind adult. *Perception*, 35(6), 847–851. doi:10.1068/p5316

Kim, S., Park, E.-S., & Ryu, E.-S. (2019). Multimedia vision for the visually impaired through 2D multiarray braille display. *Applied Sciences*, 9(5), 878. doi:10.3390/app9050878

Kitada, R. (2016). The brain network for haptic object recognition. In (pp. 21-37). Tokyo: Springer Japan. doi:10.1007/978-4-431-55772-2_2

Kitada, R., Ng, M., Tan, Z. Y., Lee, X. E., & Kochiyama, T. (2021). Physical correlates of human-like softness elicit high tactile pleasantness. *Scientific Reports*, 11(1), 16510. doi:10.1038/s41598-021-96044-w

Klatzky, R. L., & Lederman, S. J. (1988). The intelligent hand. In (Vol. 21, pp. 121–151): Elsevier Science & Technology. doi:10.1016/S0079-7421(08)60027-4

Klatzky, R. L., & Lederman, S. J. (2011). Haptic object perception: Spatial dimensionality and relation to vision. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366(1581), 3097–3105. doi:10.1098/rstb.2011.0153

Lacey, S., Peters, A., & Sathian, K. (2007). Cross-modal object recognition is viewpoint-independent. *PloS ONE*, 2(9), e890–e890. doi:10.1371/journal.pone.0000890

Lacey, S., Pappas, M., Kreps, A., Lee, K., & Sathian, K. (2009). Perceptual learning of view-independence in visuo-haptic object representations. *Experimental Brain Research*, 198(2-3), 329–337. doi:10.1007/s00221-009-

Lacey, S., Lin, J. B., & Sathian, K. (2011). Object and spatial imagery dimensions in visuo-haptic representations. *Experimental Brain Research*, 213(2), 267-273. doi:10.1007/s00221-011-2623-1

Lacey, S., & Sathian, K. (2014). Visuo-haptic multisensory object recognition, categorization, and representation. *Frontiers in Psychology*, 5, 730. doi:10.3389/fpsyg.2014.00730

Lebaz, Jouffrais, & Picard. (2012). Haptic identification of raised-line drawings: High visuospatial imagers outperform low visuospatial imagers. *Psychological Research*, 76(5), 667–675. doi:10.1007/s00426-011-0351-

Lebreton, P. (2016). Assessing human depth perception for 2D and 3D stereoscopic images and video and its relation to the overall 3D QoE. (Doctoral dissertation), Technische Universitaet Berlin, Germany. doi:10.14279/depositonce-5126

Lederman, S. J., Klatzky, R. L., Chataway, C., & Summers, C. D. (1990). Visual mediation and the haptic recognition of two-dimensional pictures of common objects. *Perception & Psychophysics*, 47(1), 54–64. doi:10.3758/BF03208164

Likova, L. T. (2012). Drawing enhances cross-modal memory plasticity in the human brain: A case study in a totally blind adult. *Frontiers in Human Neuroscience*, 6(2012), 44–44. doi:10.3389/fnhum.2012.00044

Loomis, J., Klatzky, R. L., & Lederman, S. J. (1991). Similarity of tactual and visual picture recognition with limited field of view. *Perception*, 20(2), 167–177. doi:10.1068/p200167

Mazella, A., Albaret, J.-M., & Picard, D. (2018). The development of haptic processing skills from childhood to adulthood by means of two-dimensional materials. *Canadian Journal of Experimental Psychology*, 72(1), 48–57. doi:10.1037/cep0000121

Newell, F., Ernst, M., Tjan, B., & Bülthoff, H. (2001). Viewpoint dependence in visual and haptic object recognition. *Psychological Science*, 12, 37–42. doi:10.1111/1467-9280.00307

Nguyen, A. M., Ferro, T. J., & Pawluk, D. T. V. (2018). Effectiveness of using local cues to indicate perspective in tactile diagrams for people with visual impairments. *Journal of Visual Impairment & Blindness*, 112(6), 731–744. doi:10.1177/0145482X1811200608

Occelli, V., Lacey, S., Stephens, C., John, T., & Sathian, K. (2016). Haptic object recognition is view-independent in early blind but not sighted people. *Perception*, 45(3), 337-345. doi:10.1177/0301006615614489

Overvliet, K. E., Wagemans, J., & Krampe, R. T. (2013). The effects of aging on haptic 2D shape recognition. *Psychology and Aging*, 28(4), 1057–1069. doi:10.1037/a0033415

Overvliet, K. E., & Krampe, R. T. (2018). Haptic two-dimensional shape identification in children, adolescents, and young adults. *Journal of Experimental Child Psychology*, 166, 567–580. doi:10.1016/j.jecp.2017.09.024

Pasqualotto, A., Ng, M., Tan, Z. Y., & Kitada, R. (2020). Tactile perception of pleasantness in relation to perceived softness. *Scientific Reports*, 10(1), 11189. doi:10.1038/s41598-020-68034-x

Pearson, J. (2019). The human imagination: The cognitive neuroscience of visual mental imagery. *Nature Reviews Neuroscience*, 20(10), 624–634. doi:10.1038/s41583-019-0202-9

Perini, F., Powell, T., Watt, S. J., & Downing, P. E. (2020). Neural representations of haptic object size in the human brain revealed by multivoxel fMRI patterns. *Journal of Neurophysiology*, 124(1), 218–231. doi:10.1152/jn.00160.2020

Picard, D., Lebaz, S., Jouffrais, C., & Monnier, C. (2010). Haptic recognition of two-dimensional raised-line patterns by early-blind, late-blind, and blindfolded sighted adults. *Perception*, 39(2), 224–235. doi:10.1068/p6527

Prather, S. C., Votaw, J. R., & Sathian, K. (2004). Task-specific recruitment of dorsal and ventral visual areas during tactile perception. *Neuropsychologia*, 42(8), 1079–1087. doi:10.1016/j.neuropsychologia.2003.12.013

Qian, J., & Petrov, Y. (2016). A depth illusion supports the model of general object constancy: Size and depth constancies related by the same distance-scaling factor. *Vision Research*, 129, 77–86. doi:10.1016/j.visres.2016.09.015

Roldan, S. M. (2017). Object recognition in mental representations: Directions for exploring diagnostic features through visual mental imagery. *Frontiers in Psychology*, 8(5), 833–833. doi:10.3389/fpsyg.2017.00833

Sathian, K., Lacey, S., Stilla, R., Gibson, G. O., Deshpande, G., Hu, X., . . . Glielmi, C. (2011). Dual pathways for haptic and visual perception of spatial and texture information. *NeuroImage*, 57(2), 462–475. doi:10.1016/j.neuroimage.2011.05.001

Sathian, K. (2016). Analysis of haptic information in the cerebral cortex. *Journal of Neurophysiology*, 116(4), 1795–1806. doi:10.1152/jn.00546.2015

Senna, I., Andres, E., McKyton, A., Ben-Zion, I., Zohary, E., & Ernst, M. O. (2021). Development of multisensory integration following prolonged early-onset visual deprivation. *Current Biology*, 31(21), 4879–4885.e4876. doi:10.1016/j.cub.2021.08.060

Sheldon, S., Amaral, R., & Levine, B. (2017). Individual differences in visual imagery determine how event information is remembered. *Memory*, 25(3), 360–369. doi:10.1080/09658211.2016.1178777

Sinha, P., & Kalia, A. A. (2012). Tactile picture recognition: Errors are in shape acquisition or object matching? *Seeing and Perceiving*, 25(3-4), 287–302. doi:10.1163/187847511X584443

Stoesz, M. R., Zhang, M., Weisser, V. D., Prather, S. C., Mao, H., & Sathian, K. (2003). Neural networks active during tactile form perception: Common and differential activity during macrospatial and microspatial tasks. *International Journal of Psychophysiology*, 50(1), 41–49. doi:10.1016/S0167-8760(03)00123-5

Szubielska, M., Niestorowicz, E., & Marek, B. (2019). The relevance of object size to the recognizability of drawings by individuals with congenital blindness. *Journal of Visual Impairment & Blindness*, 113(3), 295–310. doi:10.1177/0145482x19860015

Tarr, M. J., & Hayward, W. G. (2017). The concurrent encoding of viewpoint-invariant and viewpoint-dependent information in visual object recognition. *Visual Cognition*, 25(1-3), doi:10.1080/13506285.2017.1324933

Theurel, A., Witt, A., Claudet, P., Hatwell, Y., & Gentaz, E. (2013). Tactile picture recognition by early blind children: The effect of illustration technique. *Journal of Experimental Psychology: Applied*, 19(3), 233–240. doi:10.1037/a0034255

Thompson, L. J., Chronicle, E. P., & Collins, A. F. (2006). Enhancing 2-D tactile picture design from knowledge of 3-D haptic object recognition. *European Psychologist*, 11(2), 110–118. doi:10.1027/1016-9040.11.2.110

Toprak, S., Navarro-Guerrero, N., & Wermter, S. (2018). Evaluating integration strategies for visuo-haptic object recognition. *Cognitive Computation*, 10(3), 408–425. doi:10.1007/s12559-017-9536-7

Vinter, A., Bonin, P., & Morgan, P. (2018). The severity of the visual impairment and practice matter for drawing ability in children. *Research in Developmental Disabilities*, 78, 15–26. doi:10.1016/j.ridd.2018.04.027

Vinter, A., Orlandi, O., & Morgan, P. (2020). Identification of textured tactile pictures in visually impaired and blindfolded sighted children. *Frontiers in Psychology*, 11, 345. doi:10.3389/fpsyg.2020.00345

Wan, C., Cai, P., Guo, X., Wang, M., Matsuhisa, N., Yang, L., Lv, Z., Luo, Y., Loh, X. J., & Chen, X. (2020). An artificial sensory neuron with visual-haptic fusion. *Nature Communications*, 11(1), 4602. doi:10.1038/s41467-020-18375-y

Withagen, A., Kappers, A. M. L., Vervloed, M. P. J., Knoors, H., & Verhoeven, L. (2013). The use of exploratory procedures by blind and sighted adults and children. *Attention, Perception & Psychophysics*, 75(7), 1451–1464. doi:10.3758/s13414-013-0479-0

Woods, A. T., Moore, A., & Newell, F. N. (2008). Canonical views in haptic object perception. *Perception*, 37(12), 1867–1878. doi:10.1068/p6038

Yang, J., Yu, Y., Kunita, A., Huang, Q., Wu, J., Sawamoto, N., & Fukuyama, H. (2014). Tactile priming modulates the activation of the fronto-parietal circuit during tactile angle match and non-match processing: An fMRI study. *Frontiers in Human Neuroscience*, 8, 926–926. doi:10.3389/fnhum.2014.00926

Yasaka, K., Mori, T., Yamaguchi, M., & Kaba, H. (2019). Representations of microgeometric tactile information during object recognition. *Cognitive Processing*, 20(1), 19–30. doi:10.1007/s10339-018-0892-3

Yau, J. M., Kim, S. S., Thakur, P. H., & Bensmaia, S. J. (2016). Feeling form: The neural basis of haptic shape perception. *Journal of Neurophysiology*, 115(2), 631–642. doi:10.1152/jn.00598.2015

Yoshida, T., Yamaguchi, A., Tsutsui, H., & Wake, T. (2015). Tactile search for change has less memory than visual search for change. *Attention, Perception & Psychophysics*, 77(4), 1200–1211. doi:10.3758/s13414-014-0829-

Yu, J., Wu, Q., Yang, J., Takahashi, S., Ejima, Y., & Wu, J. (2017, August). A study of shape discrimination for tactile guide maps. In 2017 IEEE International Conference on Mechatronics and Automation (ICMA)(pp. 565–570). IEEE. doi: 10.1109/ICMA.2017.8015879

Zhang, Q., & Li, S. (2020). The roles of spatial frequency in category-level visual search of real-world scenes. *PsyCh Journal*, 9(1), 44–55. doi:10.1002/pchj.294

Note: Figure translations are in progress. See original paper for figures.