Acta Psychologica 130 (2009) 251–259

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Haptic mental rotation revisited: multiple reference frame dependence

Robert Volcic [a,b,*], Maarten W.A. Wijntjes [a,c], Astrid M.L. Kappers [a]

[a] Helmholtz Institute, Utrecht University, Padualaan 8, 3584 CH Utrecht, The Netherlands
[b] Psychologisches Institut II, Westfälische Wilhelms-Universität, Fliednerstrasse 21, 48149 Münster, Germany
[c] Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands

ARTICLE INFO

Article history:
Received 2 May 2008
Received in revised form 11 December 2008
Accepted 20 January 2009
Available online 24 February 2009

PsycINFO classification:
2320

Keywords:
Touch
Haptic
Mental rotation
Frame of reference
Space
Hand

ABSTRACT

The nature of reference frames involved in haptic spatial processing was addressed by means of a haptic mental rotation task. Participants assessed the parity of two objects located in various spatial locations by exploring them with different hand orientations. The resulting response times were fitted with a triangle wave function. Phase shifts were found to depend on the relation between the hands and the objects, and between the objects and the body. We rejected the possibility that a single reference frame drives spatial processing. Instead, we found evidence of multiple interacting reference frames with the hand-centered reference frame playing the dominant role. We propose that a weighted average of the allocentric, the hand-centered and the body-centered reference frames influences the haptic encoding of spatial information. In addition, we showed that previous results can be reinterpreted within the framework of multiple reference frames. This mechanism has proved to be ubiquitously present in haptic spatial processing.

1. Introduction

Any spatial characteristic of an object can only be defined relative to some reference frame, but there are in fact multiple reference frames through which the human system is able to encode objects. For instance, visual information of an object is acquired in retinocentric coordinates, but it can be also encoded in head-centered coordinates to stabilize perception during eye movements, or in body-centered coordinates to allow the perceiver to act on that object. The object can also be encoded relative to the environment in an allocentric reference frame. Similarly, haptic information is usually gathered via the hand, the primary sense organ for touch. The spatial information in hand-centered coordinates is then transposed to hierarchically higher reference frames to fulfill the needs of an active human system. In general, the perceiver's behavior based on both visual and haptic spatial information is assumed to be a result of processes that combine the different frames of reference within each modality as well as between modalities.

Whenever we touch an object we establish a relation between the perceiving hand and the object, and consequently the orientation of the object with respect to the hand can be obtained from this relation. To extract the spatial characteristics of the object in the environment (i.e., its orientation and its location), additional relations have to be established also between the perceiving hand and the perceiver, and between the perceiver and the surrounding environment. From this point of view, it can be hypothesized that multiple encodings of the same object coexist simultaneously. For instance, Oldfield and Philips (1983) proposed that haptic perception of an object involves both an egocentric frame and an allocentric frame of reference, and that it is the relative position of the egocentric reference frame within the allocentric reference frame that determines the perceptual experience. Similar conclusions were reached also in studies where the task was to identify letters or numbers traced on surfaces of the perceiver's body when the relative spatial orientations and positions of the body surfaces and of the stimuli varied (Corcoran, 1977; Duke, 1966; Krech & Crutchfield, 1958; Natsoulas & Dubanoski, 1964; Parsons & Shimojo, 1987).

The role of reference frames in haptic perception was highlighted in a series of studies investigating the spatial relations between objects (Kappers, 1999; Kappers & Koenderink, 1999; for a review, see Postma, Zuidhoek, Noordzij, & Kappers, 2008). Systematic deviations were observed in the task where blindfolded participants were asked to align two objects in such a way that they felt parallel to each other. The two objects had to diverge away from the body, on average by about 50°, to be

* Corresponding author. Address: Psychologisches Institut II, Westfälische Wilhelms-Universität, Fliednerstrasse 21, 48149 Münster, Germany. Tel.: +49 251 83 34177.
E-mail address: volcic@psy.uni-muenster.de (R. Volcic).

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doi:10.1016/j.actpsy.2009.01.004

perceived as parallel. A biasing effect of the hand orientation was pinpointed as the dominant factor (Kappers, 2004, 2005; Kappers & Viergever, 2006; Volcic, Kappers, & Koenderink, 2007). As a further step, an interaction between the hand-centered egocentric reference frame and the allocentric reference frame was presupposed and subsequently the deviations were successfully described both in two and in three dimensions with a weighted average model that balances the contributions of the two reference frames (Kappers, 2007; Volcic & Kappers, 2008). These studies have shown the primary role of the hand-centered egocentric reference frame in the encoding of information about objects and how influential this encoding can be in haptic spatial processing.

The interplay of reference frames has also been demonstrated in mental rotation tasks. In vision, for example, different studies have attempted to discover which reference frame is used in a mental rotation task by dissociating the retinal upright from the gravitational upright by having participants tilt their heads in certain conditions (Corballis, Nagourney, Shetzer, & Stefanatos, 1978; Corballis, Zbrodoff, & Roldan, 1976). Response times are generally fastest when stimuli are perfectly aligned with the perceptual reference frame. In addition, the degree of misalignment between the orientation of the stimulus and the orientation of the frame produces a linear increase in response time. On the basis of these premises, it is possible to derive in which perceptual reference frame the stimuli are actually encoded. For instance, when the head is tilted, stimuli in gravitational upright orientation are responded to most quickly and response times increase as a function of the misalignment from this orientation. This pattern of response times is consistent with the use of an allocentric, gravitationally aligned, reference frame. On the other hand, a pattern of response times shifted to match the retinally upright orientation is consistent with the use of an egocentric, retinally aligned, reference frame. Corballis et al. (1976, 1978) showed that stimuli tend to be encoded in a reference frame midway between the egocentric and the allocentric reference frames, where the latter one is more dominant. McMullen and Jolicoeur (1992) reached similar conclusions.

In a similar fashion, the mental rotation task has been employed to identify the reference frame in which objects are haptically encoded. Carpenter and Eisenberg (1978) presented a single letter haptically in a normal or mirror-image form in various orientations. Participants had to retrieve from memory the letter in its canonical orientation and compare it with the presented letter to decide whether the letter was normal or a mirror image. One of the purposes of their study was to investigate the influence of hand position. They varied the orientation of the hand relative to the participant's body in two conditions while keeping the stimulus in the same location. In the first condition the right hand was parallel to the participant's midsagittal plane, whereas in the second condition the right hand was rotated counterclockwise by 60°. The influence of hand position was evident from the patterns of the response time functions that differed in their phase shift. In both conditions the fastest response time was observed when the hand was aligned with the stimulus, and response times increased with larger differences in orientation between the stimulus and the hand. This means that whereas in the first condition the fastest response time was measured when the major axis of the stimulus was parallel to the participant's midsagittal plane, in the second condition the stimulus had to be rotated by approximately 60°. On the basis of these results, Carpenter and Eisenberg (1978) concluded that the orientation of a letter is encoded with respect to a hand-centered reference frame.

A more recent study on haptic mental rotation led Prather and Sathian (2002) to different conclusions. They applied an embossed letter on the participant's finger pad and, as in Carpenter and Eisenberg (1978), participants had to determine if the letter was normal or a mirror image. In one condition the finger pad was positioned horizontally in front of the participant, centered in the midsagittal plane and parallel to it, whereas in the second condition the finger pad was also centered in the midsagittal plane but orthogonal to it. Despite the change in the orientation of the finger pad and, consequently, in the orientation of the hand, the response time functions in the two conditions were very similar. Prather and Sathian (2002) concluded that haptic stimuli are not encoded in a hand-centered reference frame and suggested that the encoding might occur in a body-, head- or eye-centered reference frame. In addition, they supposed that the phase shift in the direction of the hand orientation found by Carpenter and Eisenberg (1978) could be accounted for by a head-centered reference frame if participants kept their head in alignment with their hand.

The main aim of the present paper was to experimentally disentangle the different reference frames that may play a role in haptic mental rotation and, generally, in haptic spatial processing. To pursue this purpose we used a bimanual mental rotation task that requires participants to determine whether two objects of the same shape and in different orientations felt by the two hands are mirror images of each other or identical except for orientation. This task is also known as the handedness recognition task and it is a widely used task in mental rotation studies since its introduction by Shepard and Metzler (1971). In this way, objects can be directly compared with each other in contrast to the comparison between the stimulus and its memory-based representation as was the case in all the earlier studies on haptic mental rotation. We restricted our quest to a group of reference frames that are most likely involved in haptic spatial processing: the allocentric, the hand-centered egocentric and the body-centered egocentric reference frames. In the allocentric reference frame, objects are represented relative to the environment that is extrinsic to the perceiver. In the hand-centered egocentric reference frame, objects are represented relative to the perceiver's hand and, finally, in the body-centered egocentric reference frame, objects are represented relative to the perceiver's body. Our definition of the latter reference frame comprises also a head-centered reference frame as long as the head faces forward. To dissociate the influences of the different reference frames, we devised different experimental conditions in which the two objects to be compared were explored with different hand orientations and were located in different positions relative to the perceiver's body (see Fig. 1, left panel). We expected that the employment of the relevant reference frame would evince itself in a specific phase shift of the response time function. In the simplest case, if only an allocentric reference played a role, the quickest response time should be observed when the two objects are physically aligned. Response times would linearly increase, both in the positive and in the negative directions, as a function of an increase in the orientation difference between the two objects. This pattern, i.e., a response time function with no phase shift, would be independent of the experimental condition and it is exemplified in the leftmost column in Fig. 1 (right panel). This is essentially similar to the Shepard and Metzler (1971) model. They used a linear function to model response times. The triangle wave function is the generalized version of this function taking into account the periodicity. Predictions that are dependent on the experimental condition could be made for the cases in which either the hand-centered or the body-centered reference frame would play a role in haptic mental rotation. The response time function was expected to shift horizontally (phase shift) depending on the positions of the hands or on the position of the objects with respect to the body (see center and rightmost columns in Fig. 1, right panel). For example, if the body-centered