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Research report

How coordinate and categorical spatial relations combine with egocentric and allocentric reference frames in a motor task: Effects of delay and stimuli characteristics

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HIGHLIGHTS

- Egocentric–allocentric frames were combined with categorical–coordinate relations.
- Participants performed a pointing task according to four spatial instructions.
- Stimuli characteristics and delay between learning and testing were manipulated.
- The use of 3D stimuli and immediate response favors egocentric coordinate judgments.
- 2D stimuli and delayed response improve allocentric and categorical representations.

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ABSTRACT

This study explores how people represent spatial information in order to accomplish a visuo-motor task. To this aim we combined two fundamental components of the human visuo-spatial system: egocentric and allocentric frames of reference and coordinate and categorical spatial relations. Specifically, participants learned the position of three objects and then had to judge the distance (coordinate information) and the relation (categorical information) of a target object with respect to themselves (egocentric frame) or with respect to another object (allocentric frame). They gave spatial judgments by reaching and touching the exact position or the side previously occupied by the target object. The possible influence of stimuli characteristics (3D objects vs. 2D images) and delay between learning phase and testing phase (1.5 vs. 5 s) was also assessed. Results showed an advantage of egocentric coordinate judgments over the allocentric coordinate ones independently from the kind of stimuli used and the temporal parameters of the response, whereas egocentric categorical judgments were more accurate than allocentric categorical ones only with 3D stimuli and when an immediate response was requested. This pattern of data is discussed in the light of the "perception-action" model by Milner and Goodale [13] and of neuroimaging evidence about frames of reference and spatial relations.

1. Introduction

In order to deal with a variety of daily tasks, people need to use spatial information about objects in the environment. For example, if we are looking for the car keys we need to remember "where" we left them the last time (e.g. on the desk), and if we decide to reach for and grasp them we need to specify "where" they are with respect to our body. These examples show that human beings commonly use two kinds of frames of reference to encode and mentally represent the locations of objects: an *egocentric* frame of reference that specifies where an object is with respect to the body and an *allocentric* frame of reference that specifies where an object is with respect to another one in the external world [for reviews: 1–2]. Moreover, the kind of spatial relation represented through an egocentric or an allocentric frame of reference can be defined as *coordinate* if it is based on a fine-grained metric code that allows for precise distance

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discriminations between objects' positions, or *categorical* if a more abstract code is used (e.g. left\right; above\below) which delimitates areas in the outside world in which all possible locations can be treated as more or less equivalent and provides nonmetric localizations [3–5].

It has been recently shown that egocentric and allocentric frames of reference (FoR) and categorical and coordinate spatial relations (SR) represent distinct but somehow interacting components of human visuo-spatial system whose combination gives rise to four kinds of spatial representations: egocentric coordinate (e.g. object *X* is closer to me than object *Y*), egocentric categorical (e.g. both objects *X* and *Y* are on my right), allocentric coordinate (e.g. object *X* is closer to object *Y* than object *Z*), and allocentric categorical (e.g. both objects X and *Y* are on the right of object *Z*). It has been suggested that the functioning of these four spatial representations is not independent of the purpose and the characteristics of the task at hand [6]. However, the characteristics of the task that favor a kind of spatial representation rather than another one have not yet been fully explored. Indeed, egocentric and allocentric frames of reference have usually been studied separately from categorical and coordinate spatial relations. As a consequence, much evidence has been collected regarding the factors that could influence the encoding of spatial locations in egocentric and\or allocentric terms (e.g.: – people's age [7,8]; – way of learning [9]; – size [10]; – geometric structure of the environment [11]; – familiarity with the environment [12]), but their relationship with categorical\coordinate spatial relations has not received much attention.

As regards the relationship between FoR and SR, literature suggests some functional similarities. According to the "two-visual stream hypothesis" proposed by Milner and Goodale [13–15], allocentric and egocentric frames of reference have a clear and distinct functional role within perceptual- and action-oriented tasks. Specifically, the vision-for-action subsystem (dorsal stream) would privilege egocentric frames of reference for controlling movements in space. Instead, the vision-for-perception subsystem (ventral stream) is related to visual consciousness and to memory systems, and would privilege allocentric frames of reference. Importantly, similar functions have been attributed to the coordinate and categorical spatial relations respectively. According to Kosslyn [3,16], categorical information is more useful for object recognition, whereas coordinate spatial relations are more useful for accurately reaching elements in the space (object or places). The functional link between egocentric and coordinate components on a side and allocentric and categorical dimensions on the other has also been suggested by Milner et al. [17–19]. The rationale behind this association is that the visuo-perceptual system would codify object-to-object relationships and at the same time would use a kind of "abstract" coding (e.g. "left of", "above") for recognition purposes. This kind of coding would ensure that changes in the relative location of the target with respect to the observer, due to movements of the observer, do not change the perceived spatial location of object. This "space constancy" would also provide observers with an awareness of the relative locations of two or more objects, even if they are out of sight. Instead, when we decide to look and reach for a specific object, dorsal sensorimotor systems which process metric spatial information in egocentric terms are engaged.

In our recent works [6,20], we explored the relationship between FoR and SR by asking participants to give categorical (*same side or not?*) and coordinate (*same distance or not?*) visuo-perceptual judgments about two vertical bars with respect to an allocentric (*a horizontal bar*) or an egocentric (*their body-midline*) frame of reference. Results showed that allocentric judgments were better when combined with categorical than coordinate spatial relations, however no advantage for coordinate judgments when combined with an egocentric rather than an allocentric frame appeared. We reasoned that these results could have been due to the fact that participants were only requested to visually estimate distances of the two vertical bars and to report a "true or false" response by pressing a mouse pad button. Instead, according to the above mentioned theoretical proposals an egocentric representation of coordinate relations should be favored if people are requested to make a movement toward an object in the environment. In line with this, several behavioral studies have highlighted the relevance of egocentric processing of spatial information for motor tasks (e.g. reaching and pointing a location in the space) more than for visuo-perceptual judgments (e.g. judgments of spatial locations with a verbal response or pressing of response keys). For example, it has been shown that irrelevant allocentric information affects visuo-perceptual judgments about spatial properties of target objects, but this allocentric influence decreases when visually driven pointing movements toward the same target objects are required [21]. This has been interpreted as a consequence of the fact that pointing movements mainly require the encoding of target-object's spatial properties with respect to the body or parts of it, that is in egocentric terms (for a review about pointing task: [22]; but see also Ref. [23]). However, it has also been shown that visuo-motor responses can be influenced by allocentric irrelevant information (or background information) if a delay is interposed between stimulus presentation and response. This is thought to happen because egocentric representations are transient and not durable (at least no more than 2.5 s; but see Ref. [24]), whereas allocentric information would involve long-term representations. As a consequence, when a movement toward a target is programmed on the basis of memory, allocentric information becomes more relevant and it is combined with egocentric information for guiding the action [21,25,26]. Interestingly, some studies have shown temporal thresholds also for coordinate and categorical spatial relations: coordinate representations seem to decay more rapidly than categorical representations [27,28].

In sum, these studies seem to suggest that an egocentric representation of coordinate spatial relations should be favored when people make a movement toward an object (e.g. reaching for a specific object) immediately (or at least within 2.5 s) after the presentation of the object. Instead, allocentric representations of categorical spatial relations can be favored if the movement toward the object is memory driven, that is at least after 2.5 s from the object's disappearance.

Another factor that could influence the way people represent spatial properties of a configuration of objects is represented by the characteristics of the objects themselves. For example, it has been demonstrated that the only vision of manipulable objects activates parietal, dorsal premotor, and inferior frontal cortex and prompts motor simulation processes even in the absence of any intention to act [29–34]. Interestingly, similar neural activations have often been found in association with egocentric representations [35–38]. On the contrary, observing non-manipulable stimuli does not activate motor components.

Therefore, the aim of this study was to verify if the way people represent spatial information to guide a movement toward a location in the space is influenced by the temporal parameters of the motor response and by stimuli's characteristics. To this aim we adapted the Ego-Allo/Cat-Coor task proposed by Iachini and Ruggiero [39] (see also Ref. [40]). This task assesses the capacity to use egocentric and allocentric frames of reference in combination with categorical and coordinate spatial relations. For instance, it requires explicitly the encoding of distances (coordinate) or relations (categorical) with respect to the participant's body (egocentric) or to an external object (allocentric). This kind of experimental paradigm has already been used to assess spatial memory in healthy adults [39], brain damaged patients [40,41], blind people [42–44], children with cerebral palsy [45,46], in a fMRI study [35], and has proved its efficacy in inducing a specific involvement of spatial frames of reference.