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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

Francesco Ruotolo[a,b,*], Ineke van der Ham[a], Albert Postma[a], Gennaro Ruggiero[b], Tina Iachini[b]

[a] Department of Experimental Psychology, University of Utrecht, The Netherlands
[b] Laboratory of Cognitive Science and Immersive Virtual Reality, Second University of Naples, Italy

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

* Corresponding author at: University of Utrecht, Department of Experimental Psychology, Heidelberglaan 1, 3584 CS Utrecht, The Netherlands. Tel.: +31 030 2534023; fax: +31 030 2534511.
E-mail address: f.ruotolo@uu.nl (F. Ruotolo).

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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.

In this study a group of participants was required to learn the position of three geometrical objects ("3-D" condition), whereas another one group learned the position of three two-dimensional geometric images ("2-D" condition). Next the objects or images were removed and participants were asked to indicate by reaching and touching with the index finger the position of the object\image closest or farthest to them (*egocentric coordinate* task) and to another object\image (*allocentric coordinate* task). Moreover, they were requested to indicate where a target object\image was with respect to them (right or left?) (*egocentric categorical* task) and with respect to another object\image (right or left?) (*allocentric categorical* task). In both 3-D and 2-D conditions, participants were divided in two subgroups: a subgroup was requested to give the answer immediately after (i.e. after 1.5 s) stimuli removal ("Immediate" response), whereas the other subgroup to give the answer after 5 s stimuli were removed ("Delayed" response).

As this was a motor task, we expected a general advantage of egocentric rather than allocentric organization of spatial information, and this would have been particularly true with coordinate rather than categorical spatial relations. However, we also expected that the combination between FoR and SR would have been modulated by the temporal parameters of the response and stimuli's characteristics. On the basis of the literature, the use of 3D manipulable stimuli and an immediate response was supposed to stress the dorsal stream of the brain and as a consequence favor an egocentric representation of coordinate relations, whereas a delayed response and 2D images were supposed to improve allocentric organization of categorical spatial relations.

To verify these hypotheses, two main Experiments (Experiments 1 and 2) and two control experiments were carried out. Experiments 1 and 2 only differed in the kind of stimuli used: 3D manipulable stimuli for Experiment 1 and 2D images of the same stimuli for Experiment 2.

2. Experiment 1

2.1. Materials and methods

2.1.1. Participants

Forty-eight students from the Second University of Naples participated in the experiment in exchange for course credit or a small amount of money. They were randomly attributed to one of the two experimental conditions but matched on the basis of sex and age: "Immediate" condition (12 men and 12 women, mean age = 23.40, SD = 2.80; range: 20–28); "Delayed" condition (12 men and 12 women, mean age = 21.40, SD = 3.80; range: 22–27). All participants were right handed and had a normal or corrected to normal vision. Recruitment and testing were in conformity with the requirements of the Ethical Committee of the Second University of Naples, of the Ethical Committee of the Faculty of Social and Behavioral Sciences of Utrecht University, and of the 2013 Declaration of Helsinki.

2.1.2. Stimuli and setting

The experiment was carried out in a soundproofed, comfortable room.

Participants sat on a straight-back chair placed centrally at 30 cm from the edge of a small desk measuring 50 cm (width) × 35 cm (length).

Materials and procedure were the same used by Iachini et al. [39,40]. The stimuli comprised easily nameable and well-known 3D geometrical objects such as pyramid, parallelepiped, cone, cube, sphere, and cylinder presented with two sizes: big (8 cm × 8 cm, except parallelepiped and cylinder: 8 cm × 11 cm) and small (6 cm × 6 cm, except parallelepiped and cylinder: 6 cm × 9 cm). The objects differed in color: dark, medium and light gray. By combining objects, size and color, 9 objects for each series were selected (e.g., the Cone could be big-dark, etc.). The combination was such that 18 objects were obtained, subdivided in two series ((A) Pyramid, Parallelepiped, and Cone and (B) Cube, Sphere, and Cylinder). Still, each series was subdivided in 3 triads. Each triad had a target-object (T) that is the object with respect to which the allocentric judgments were given. Each triad was arranged on the desk on a plasterboard panel (50 cm × 30 cm × 2 cm) according to the following criteria: (1) inter-objects metric distances had to be easily distinguishable; (2) the metric distances were established in such a way that the amount of metric difficulty was the same for egocentric and allocentric judgments. The metric difficulty was related to the amount of distance between stimuli. An example of triad and related inter-objects and participant-objects distances are given in Fig. 1a and b. In Fig. 1b, the distances between the stimuli were: cylinder–cube = 15 cm; pyramid–cube = 10 cm; cylinder–pyramid = 30 cm. The cylinder and pyramid were respectively 5 cm and 10 cm far from the body. The cube was the target (i.e. the point of reference) for the allocentric judgments. The metric difference between the two objects closer to the body was 5 cm (10–5 = 5) and corresponded to that of the cube and the other two objects (10 − 5 = 5). In another triad, for example, the distances were the following: sphere–cylinder = 22 cm; cylinder–cube = 12 cm; cube–sphere = 32 cm; allocentric target = cylinder; sphere and cube were 4 cm and 14 cm far from the body; egocentric and allocentric metric difficulty corresponded to 10 cm. The remaining triads were arranged similarly to the examples reported here with a metric difficulty ranging from 5 to 10 cm. The same logic is applied to

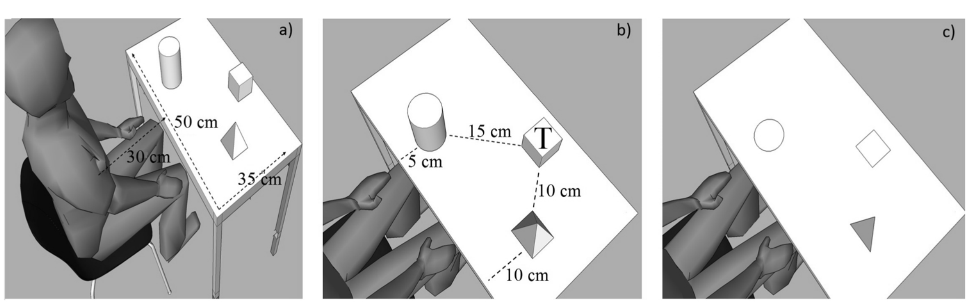

Fig. 1. The figure depicts the experimental setting and the stimuli used in the study. (a) Participant seated at 30 cm of distance from the edge of the desk. The center of the desk was aligned with participant's body-midline; (b) the 3D geometrical objects of the Experiment 1 were positioned on the desk in a way that the metric difficulty for allocentric and egocentric judgments was the same for each triad (e.g. in Fig. 1b the cube was the allocentric target (T) and the metric difficulty for allocentric coordinate judgment corresponded to 5 cm (15 cm–10 cm); the egocentric metric difficulty due to the cylinder and pyramid distances from the body was also 5 cm (10 cm–5 cm). The same logic applies to the categorical judgments: in (1b) the target for the egocentric categorical judgment is the "cylinder" that is at 10 cm from the extension of the body-midline (not indicated in the figure), whereas for the allocentric categorical judgment (e.g. where was the pyramid with respect to the cube? Right or left?) the target was the "pyramid" that is 10 cm away from the cube); (c) this part of the figure shows the stimuli used for Experiment 2: 2D geometrical images were used instead of 3D objects.

the categorical judgments, but in this case the distance from the extension of the body midline is considered. For example, if the target object was 10 cm on the right of another object in the allocentric judgments ("Where was the pyramid with respect to the cube? Right or left?"), the target object for egocentric categorical judgments was also at 10 cm (i.e. right or left).

The arrangement of the materials was based on pilot studies presented in previous reports [39,44]. To guarantee that all triads were presented in the same way for all participants, each triad was presented by means of a panel with the same size of the desk placed in front of participants. On this panel, the shape forming the basis of each object was engraved and the corresponding object was placed there.

2.1.3. Procedure

Two experimenters (here indicated as 1 and 2) were involved in this study and they were both unaware of the experiments purposes. Participants were first given written instructions describing the experimental procedure, then there was a training session using three common objects (e.g., a glass, a cup, and a small box). Afterwards, all experimental stimuli were presented and participants had to name them. In this way, difficulties due to naming problems could be excluded. Finally, the experiment started.

2.1.3.1. Learning phase. Experimenter 1 told participant to close the eyes while Experimenter 2 posited the panel on the desk. Afterwards, Experimenter 1 asked participants to open their eyes and memorize (6 s) the three objects presented on the panel and their positions. Learning time was checked by Experimenter 1 with a stopwatch. It was activated as soon as participant opened their eyes and stopped after 6 s. After the 6 s learning, Experimenter 1 asked participants to close their eyes while Experimenter 2 removed the panel with the objects from the desk. Next, the testing phase began after 1.5 s or after 5 s from stimuli removal according to the experimental condition (Immediate vs. Delayed condition) (see Fig. 2).

2.1.3.2. Testing phase. After memorizing a triad, participants had to provide a motor judgment in response to one of the four kinds of instructions: (a) egocentric–coordinate (Ego-Coor), "Where was the object closest (or farthest) to you?"; (b) egocentric–categorical (Ego-Cat), "Where was the cube with respect to you?"; (c) allocentric–coordinate (Allo-Coor), "Where was the object closest (or farthest) to the target (e.g., cylinder)?"; and (d) allocentric–categorical (Allo-Cat), "Where was the cylinder with respect to the target (e.g., cube)?". Importantly, Experimenter 1 asked for the spatial judgments by using only two words: "Closest-YOU" or "Farthest-YOU" for egocentric coordinate judgment, "Closest-OBJECT X" or "Farthest-OBJECT X" for allocentric coordinate judgment, "Object X-YOU" for egocentric categorical judgments, "Object X-OBJECT Y" for allocentric categorical judgments. These instructions were explained in the training session and allowed to ask for spatial judgments in a very short delay (about 700 ms for each instruction). Participants were explicitly requested to be as precise as possible when they had to indicate the object closest\farthest to them or to another object. Instead, as regards categorical judgments participants were told that it was sufficient to indicate the side (right or left) in which the required object had been presented. In the "Immediate condition", instructions were given after 1.5 s from stimuli disappearance, whereas in the "Delayed condition" instructions were given after 5 s. It is important to notice that participants did not know in advance what of the four spatial judgments they would have been requested.

Soon after Experimenter 1 gave the instructions for the spatial judgment (i.e. the two words indicated above) a stopwatch was activated and participants started the motor response. By using the index finger of their dominant arm, participants had to point and touch on the desk the position previously occupied by the center of the required object.

Once participants had touched the required position, Experimenter 1 stopped the stopwatch and asked participants to close their eyes and to let the finger on the panel. At this point, Experimenter 1 used a ruler to take the coordinates (X, Y) of the indicated positions (see Fig. 3). Experimenter 2 signed on a sheet the response time and the coordinates. A total of 24 pointing responses were given (6 responses for each kind of judgment). The order of

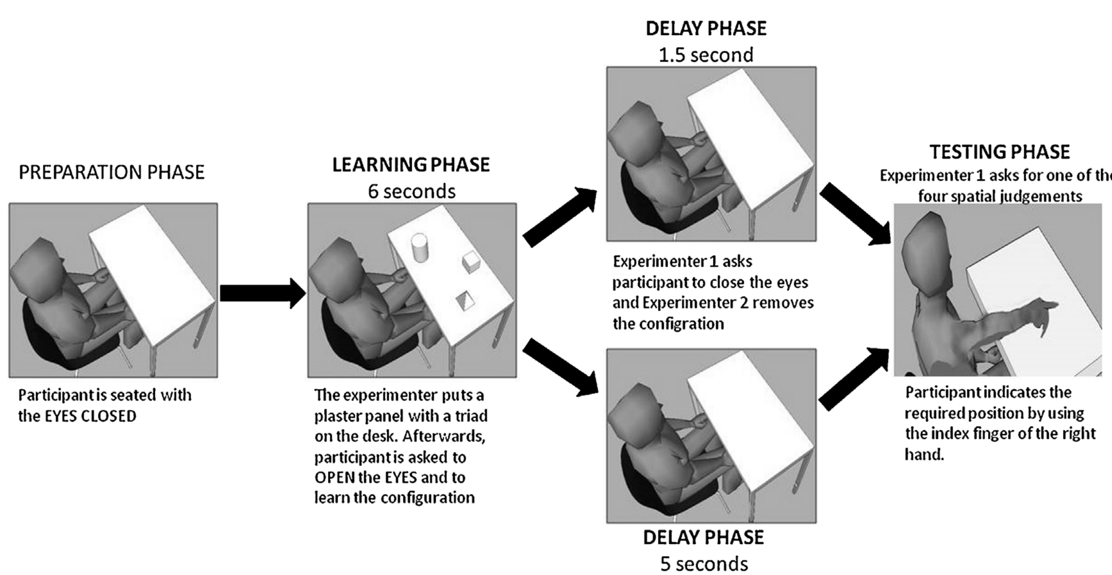

Fig. 2. The figure represents the experimental flow. During the preparation phase, participant was seated at the desk and the experimenter helped him\her to align his\her body-midline with the center of the desk. Afterwards, Experimenter 1 asked participant to close the eyes and Experimenter 2 placed the panel with the triad of objects on the desk. At this point, Experimenter 1 asked participant to open the eyes and to learn the objects and their position (learning phase) and after 6 s participant was asked to close the eyes. According to the assigned experimental condition, participants had to wait 1.5 or 5 s to receive the instructions about the kind of spatial judgment requested (Ego-Coor or Ego-Cat or Allo-Coor or Allo-Cat). During this time participant remained with eyes closed and Experimenter 2 removed the triad of objects. Finally (testing phase), Experimenter 1 asked for the spatial judgment and participant reached and touched the requested position.

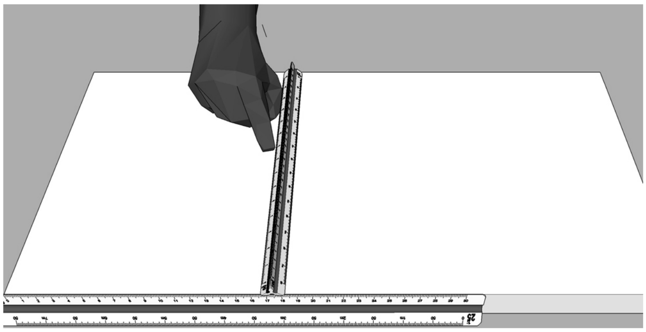

Fig. 3. The figure depicts the way Experimenters took the X and Y coordinates of the position indicated by participants. Specifically, a ruler was applied on the board of the desk opposite to the participant view (participants could not see it) indicating the X value, whereas another ruler was used to take the Y value. During this procedure participants remained with the eyes closed.

presentation of the questions was first randomized and then balanced across participants.

Three measures were scored: absolute metric error (in cm), accuracy (0/1, score range = 0–6 for each spatial combination; the mean accuracy per participant was calculated) and response time (in seconds). The absolute metric error was expressed in terms of the distance between the original position of the object on the panel ($X1$, $Y1$) and the position indicated by participants ($X2$, $Y2$). The distance (d) formula is derived from the Pythagorean Theorem (d = root square of $(X2-X1)^2+(Y2-Y1)^2$). This measure was used for coordinate judgments. Instead, as regards categorical judgments we just considered if the indicated position was on the correct side with respect to the body-midline or with respect to the requested object. It was attributed 0 for the wrong responses and 1 for each correct response.

2.2. Results

Two ANOVAs for mixed designs with frames of reference (FoR: egocentric vs. allocentric) as within factor and Delay (1.5 vs. 5 s) as between factor were carried out. The first ANOVA had the absolute metric error as dependent variable. Therefore, only egocentric and allocentric coordinate judgments were considered. Instead, in the second ANOVA the accuracy (mean of the correct responses, range: 0–1) of egocentric and allocentric categorical judgments was analyzed. The Bonferroni test was used to analyze post hoc effects. The magnitude of effect sizes was expressed by η_p^2.

2.2.1. Absolute metric error (coordinate judgments)

Results showed a main effect of FoR with egocentric judgments (M = 3.13, SD = .84) being more precise than allocentric ones (M = 9.98, SD = 4.58) ($F(1, 46) = 121.09$, $p < .001$, $\eta_p^2 = .72$). An interaction effect between FoR and Delay also appeared: $F(1, 46) = 5.14$, $p < .05$, $\eta_p^2 = .10$. The post hoc test revealed that it was due to allocentric judgments being more precise when the responses were given after 5 s (M = 8.71, SD = 3.25) than after 1.5 s (M = 11.26, SD = 5.37), whereas no difference appeared for egocentric judgments after 1.5 s (M = 2.99, SD = .94) and 5 s (M = 3.27, SD = 0.72) (see Fig. 4 left). Finally, an advantage for egocentric over allocentric judgments was found in both "Delay" conditions ($p < .001$).

2.2.2. Response time (coordinate judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 1.32, SD = .27) being faster than allocentric ones (M = 2.05, SD = .43) ($F(1, 46) = 184.04$, $p < .001$, $\eta_p^2 = .80$). No other significant effect was appeared.

2.2.3. Accuracy (categorical judgments)

Results showed a main effect of FoR with egocentric judgments (M = .94, SD = .08) being more precise than allocentric ones (M = .85, SD = .18) ($F(1, 46) = 13.31$, $p < .001$, $\eta_p^2 = .22\eta$) and a main effect of Delay due to response after 5 s (M = .95, SD = .07) being more accurate than after 1.5 s (M = .84, SD = .17) ($F(1, 46) = 16.24$, $p < .001$, $\eta_p^2 = .26$).

An interaction effect between FoR and Delay also appeared: $F(1, 46) = 11$, $p < .005$, $\eta_p^2 = .19$ (see Fig. 4 right). The post hoc test revealed that it was due to allocentric judgments being more precise when the responses were given after 5 s (M = .94, SD = .08) than after 1.5 s (M = .76, SD = .21), whereas no difference appeared for egocentric judgments after 1.5 s (M = .92, SD = .08) and 5 s (M = .95, SD = 0.7), and no difference appeared between egocentric–allocentric judgments at 5 s. Finally, allocentric judgments after 1.5 s were less accurate than all others ($p < .001$).

2.2.4. Response time (categorical judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 1.63, SD = .44) being faster than allocentric ones (M = 1.93, SD = .46): $F(1, 46) = 22.28$, $p < .001$, $\eta_p^2 = .33$) and a main effect appeared for Delay due to response after 5 s (M = 1.94, SD = .41) being slower than after 1.5 s (M = 1.62, SD = .46) ($F(1, 46) = 9.77$, $p < .005$, $\eta_p^2 = .17\eta$).

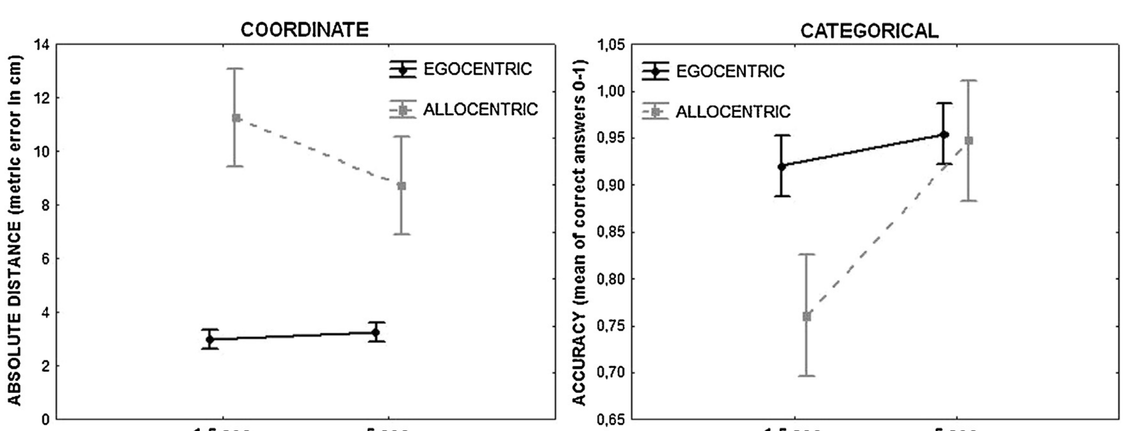

Fig. 4. The graph on the left shows the mean of metric error of egocentric and allocentric (dotted line) coordinate judgments as a function of the delay between stimuli removal and response. Instead, the graph on the right shows mean accuracy of egocentric and allocentric (dotted line) categorical judgments as a function of the delay between stimuli removal and response.

2.2.5. Discussion

For the coordinate relations results showed a general advantage of egocentric organization of spatial relations over allocentric organization. Indeed, egocentric judgments were better than allocentric ones in both "immediate" and "delayed" response conditions. However, it is important to notice that when the response was given after 5 s allocentric judgments improved. These results were in line with our hypotheses suggesting that the use of an immediate motor response toward manipulable 3D stimuli favored an egocentric organization of metric spatial information. Moreover, in line with what suggested by the "perception-action" model the introduction of a delay improved allocentric representation of spatial information and this was particularly clear when categorical spatial relations were represented. Indeed, results about categorical spatial relations showed an advantage of egocentric judgments over the allocentric ones only when the response was immediate and not when it was delayed.

Results of response times confirmed the advantage of egocentric judgments over allocentric ones by showing that egocentric judgments were faster than allocentric ones either with coordinate or categorical spatial relations.

In Experiment 2, we verified if the use of 2D stimuli facilitated allocentric representations of categorical spatial relations. The main difference between 3D and 2D stimuli was that the former had more pragmatic affordances (i.e. due to the possibility to manipulate them), whereas the latter was supposed to afford more abstract, visuo-perceptual than visuo-motor components. Therefore, due to their supposed main role in visuo-perceptual oriented task [6,13,47], we expected an advantage, or at least no difference, of allocentric categorical over egocentric categorical judgments.

3. Experiment 2

In this experiment the 3D geometrical objects of Experiment 1 were substituted with the corresponding 2D geometrical images: triangle, rectangle, circle, and square. Setting, procedure and data analysis were the same as in Experiment 1.

Moreover, to verify the effects of the kind of stimuli on the spatial representations a further analysis was carried out in which data from Experiment 2 were also analyzed in combination with data from Experiment 1 by using the characteristics of stimuli as a between factor (3D vs. 2D).

3.1. Materials and methods

3.1.1. Participants

Forty-eight students from the Second University of Naples participated in the experiment in exchange for course credit or a small amount of money. They were randomly attributed to one of the two experimental conditions but matched on the basis of sex and age: "Immediate response" condition (12 men and 12 women, mean age = 22.50, SD = 1.80; range: 20–25); "Delayed response" condition (12 men and 12 women, mean age = 20.40, SD = 3.50; range: 18–27). All participants were right handed and had a normal or corrected to normal vision.

3.1.2. Setting, stimuli, and procedure

Setting and procedure were the same of Experiment 1. Instead, the 3D objects were substituted with the corresponding 2D geometrical images (i.e. Pyramid = Triangle; Parallelepiped = Rectangle; Cube = Square; Cone = Circle; Sphere = Circle; Cylinder = Circle). Since Sphere, Cone, and Cylinder had the same 2D geometrical image (i.e. Circle), the triads presenting a combination of these three objects or two of them were not used and substituted with new triads that had the same metric difficulty of the eliminated ones. The 2-D images were drawn with a black pencil on panels of the same dimensions of those used for Experiment 1 (see Fig. 1c).

3.2. Results

Data analysis procedure was the same as in Experiment 1.

3.2.1. Absolute metric error (coordinate judgments)

Results showed a main effect of FoR with egocentric judgments (M = 3.87, SD = 1.80) being more precise than allocentric ones (M = 8.68, SD = 4.48) ($F(1, 46) = 48.62$, $p < .001$, $\eta_p^2 = .51$). No other significant effect appeared.

3.2.2. Response time (coordinate judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 1.47, SD = .37) being faster than allocentric ones (M = 1.99, SD = .37) ($F(1, 46) = 142.37$, $p < .001$, $\eta_p^2 = .75$) and a main effect of Delay due to responses after 5 s (M = 1.57, SD = .40) being faster than after 1.5 s (M = 1.90, SD = .45) ($F(1, 46) = 14.63$, $p < .001$, $\eta_p^2 = .24$).

3.2.3. Accuracy (categorical judgments)

No significant effect appeared (egocentric at 1.5 s: M = .93, SD = .11; allocentric at 1.5 s: M = .91, SD = .11; egocentric at 5 s: M = .95, SD = .12; allocentric at 5 s: M = .95, SD = .13).

3.2.4. Response time (categorical judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 1.47, SD = .37) being faster than allocentric ones (M = 1.99, SD = .37): $F(1, 46) = 30.37$, $p < .001$, $\eta_p^2 = .40$). Instead, only a tendency appeared for Delay due to responses after 5 s (M = 1.71, SD = .39) being faster than after 1.5 s (M = 1.88, SD = .40) ($F(1, 46) = 3.57$, $p = .06$, $\eta_p^2 = .07$).

3.2.5. Discussion

In line with our hypothesis, no difference appeared between egocentric and allocentric categorical judgments when the response was both delayed and immediate. The comparison with results of Experiment 1 showed that the use of 2D stimuli in Experiment 2 had favored spatial organization of categorical spatial relations according to an allocentric reference frame. Instead, an advantage of egocentric organization of spatial information over an allocentric one was present for coordinate spatial relations, as in Experiment 1. Response times showed that egocentric judgments were faster than allocentric ones and that the 5 s delay speeded up the responses.

In order to verify the effects of stimuli characteristics on the spatial judgments two ANOVAs for mixed design were carried out with FoR as within variable and delay and stimuli (2D vs. 3D) as between factors. The first analysis was carried out on absolute metric error, the second on the accuracy of categorical responses. In both cases the related response times were analyzed. The Bonferroni test was used to analyze post hoc effects. Since from these analyses appeared some effects already reported in the previous results sections of Experiments 1 and 2, only the main and\or interaction effects referred to the characteristics of stimuli (3D vs. 2D) are reported and discussed.

3.2.6. Absolute metric error (coordinate judgments)

No significant effect due to the characteristic of the stimuli appeared.

3.2.7. Response time (coordinate judgments)

Results showed an interaction effect between delay and stimuli ($F(1, 90) = 7.1$, $p < .005$, $\eta_p^2 = .073$) (see Fig. 5). The Post hoc test revealed that responses after 5 s were faster toward 2D (M = 1.57,

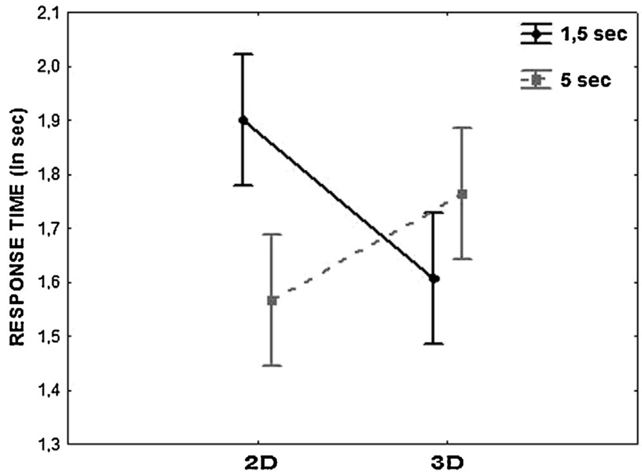

Fig. 5. The graph shows the response time of movements toward 2D and 3D stimuli as a function of the delay between learning and testing phase.

SD = .45) than 3D stimuli (M = 1.76, SD = .46) (p < .05). On the contrary, when the response was after "1.5 s" it was faster toward 3D (M = 1.62, SD = .50) than 2D stimuli (M = 1.89, SD = .40) (p < .001).

3.2.8. *Accuracy (categorical judgments)*

Results showed a 3-way interaction between FoR, Delay, and Stimuli: $F(1, 92) = 4378$, $p < .05$, $\eta_p^2 = .05$ (see Fig. 6). Post hoc test revealed that it was due to allocentric judgments toward 3D stimuli in the immediate response condition being worse than all other judgments (M = .75, SD = .23). As can be seen in Fig. 6, the 5 s of Delay specifically improved allocentric judgments toward 3D stimuli.

3.2.9. *Response time (categorical judgments)*

No significant effects appeared.

3.2.10. *Discussion*

In sum, results from this analysis showed that for coordinate spatial relations there was a general advantage of egocentric over allocentric judgments independently from the kind of stimuli used. Instead, the characteristics of the stimuli seemed to be more relevant for categorical judgments. Specifically, the combination of 3D objects and immediate response had a negative impact on allocentric categorical judgments.

Taken all together, results from Experiment 2 confirmed an advantage of egocentric coordinate judgments over allocentric ones, whereas the egocentric categorical advantage over allocentric categorical judgments depended on the characteristics of the task. If the task strongly stressed visuo-motor components by combining 3D manipulable objects with immediate motor response an egocentric advantage appeared. In contrast, the use of 2D stimuli and of a delayed response favored allocentric and categorical components.

However, one could argue that the general egocentric advantage found in both experiments could be due to some characteristics of the experimental paradigm used. Specifically, in both experiments participants remained seated in the same place for all the experiment, as a consequence participants had a clear and stable egocentric frame of reference (i.e. their body), whereas for allocentric judgments they did not know in advance what was the allocentric target that would have been used. Indeed, allocentric judgments were requested with respect one of the three objects of the configuration and it changed for each configuration. According to Waller et al. [48] the sensorimotor awareness of a stable orientation and the stability of some allocentric landmarks (e.g. the walls of the room) could favor the participants' encoding of spatial information in egocentric rather than allocentric terms [39, experiment 2]. Therefore, we decided to verify if the general advantage found in the main experiments was due to the stability of the egocentric reference frame by means of two control experiments. In the first one, we decided to make the egocentric reference frame variable by changing the position of the participant at the encoding (learning) and retrieval (testing) phases. In the second control experiment, we faced the same issue by making allocentric reference point clear and stable as the egocentric reference frame.

4. Control experiment 1

In order to verify if the stability of egocentric position influenced the pattern of data emerging from the main experiments we decided to make the egocentric position variable. In this experiment, participants learned the spatial configurations always

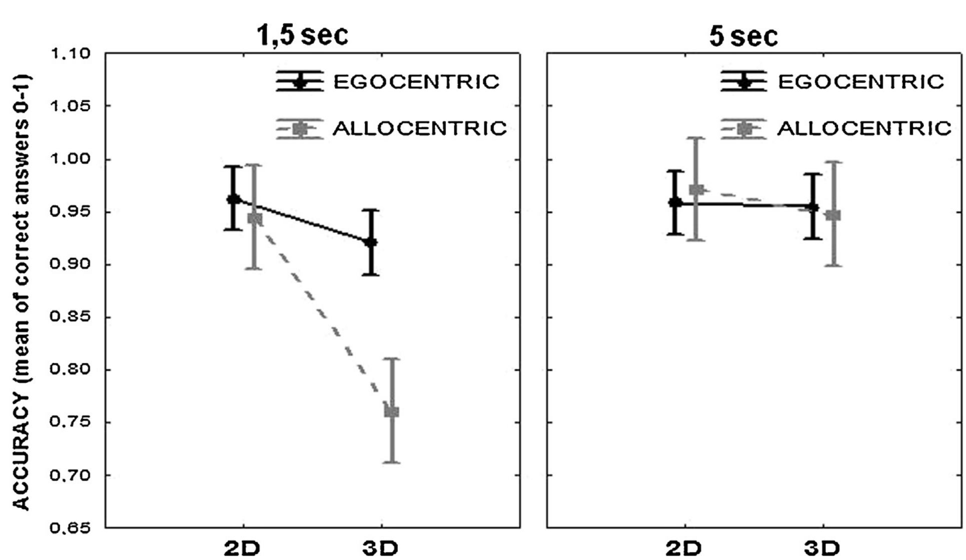

Fig. 6. The graph on the left shows accuracy mean of immediate categorical judgments (after 1.5 second) on 2D and 3D stimuli as a function of egocentric and allocentric frames of reference. Instead, the graph on the right shows accuracy mean of delayed categorical judgments (after 5 s) on 2D and 3D stimuli as a function of egocentric and allocentric frames of reference.

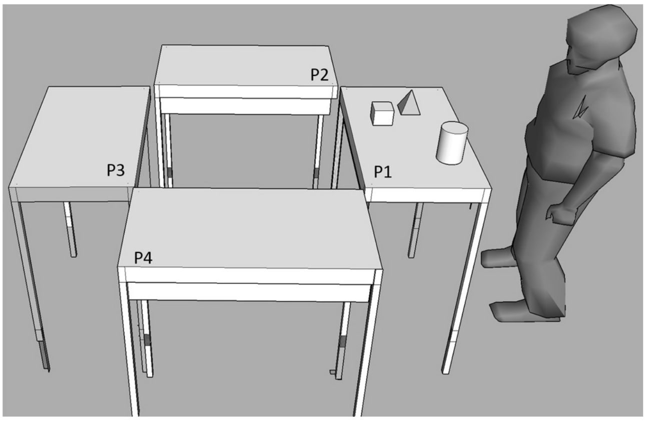

Fig. 7. The picture shows the setting used in the control Experiment 1. Participant stood upright in front of the desk and learned the position of the stimuli. Learning position (L) could be one of those indicated in the Figure (P1, P2, P3, or P4). After 6 s, the stimuli were removed and participant was conducted to one of the other three positions where the testing (T) phase started (e.g. if the learning position was P1, then the testing position could be P2, P3, or P4). The delay between learning and testing was 5 s. In no trial participants had the learning and testing phase in the same position. Once participant gave the answer, he\she was invited to close the eyes and was conducted to another learning position (e.g. P3) and then to a different testing position (e.g. P2). The combination of Learning and Testing (LT) position gave rise to six possibilities: L P1-T P2; L P1-T P3; L P1-T P4; L P2-T P1; L P2-T P3; L P2-T P4; L P3-T P1; L P3-T P4; L P3-T P2 (combinations of same testing and learning position were not used). The 24 trials were randomly associated with the six LT combinations, by paying attention that all the possible LT combinations were repeated the same number of time (i.e. every four trials had the same LT combination: $4 \times 6 = 24$ trials). The random association between LT combinations and trials was repeated for each participant.

from a different location in the room and they gave the spatial judgments always from a different position.

4.1. Materials and methods

4.1.1. Participants

Twelve-university students participated in the experiment in exchange for course credit or a small amount of money (6 men and 6 women, mean age = 25.50, SD = 4.53; range: 21–37). All participants were right handed and had a normal or corrected to normal vision.

4.1.2. Setting and stimuli

Participants were presented with the same 24 stimuli configurations used into Experiment 1 and the experiment was carried out into the same room of the main experiments. However, the experimental procedure was different. Participants stood up in front of the desk and learned the position of the presented stimuli. The desk had the same dimensions of that used in Experiment 1, but its height was arranged in a way that the distance between participants' eyes and stimuli was similar to that of Experiment 1 (see Fig. 7).

4.1.3. Procedure

Two experimenters were involved in this study and they were both unaware of the experimental purposes. Participants were first given written instructions describing the experimental procedure, then there was a training session using three common objects (e.g. a glass, a cup, and a small box). Afterwards, all experimental stimuli were presented and participants had to name them. In this way, difficulties due to naming problems could be excluded. Finally, the experiment started.

4.1.3.1. Learning phase. Experimenter 1 invited participant to stay upright in front of the desk in one of the four positions indicated in Fig. 7. Afterwards, Experimenter 1 told participant to close the eyes while Experimenter 2 posited the panel on the desk. As soon as the panel was put on the desk, Experimenter 1 asked participants to open their eyes and memorize (6 s) the three objects and their positions. After the 6 learning seconds, Experimenter 1 asked participants to close their eyes while Experimenter 2 removed the panel and conducted the participant to another of the four position into the room (it took about 5 s). Next, the testing phase began.

4.1.3.2. Testing phase. The testing phase was the same of Experiment 1 except that spatial judgments were given in a different position from the learning phase (see Fig. 7 for other details about the procedure).

4.2. Results

Two ANOVAs for repeated measures with Frames of reference (FoR: egocentric vs. allocentric) as within variable were carried out. The first ANOVA had the absolute metric error as dependent variable. Therefore, only egocentric and allocentric coordinate judgments were considered. Instead, in the second ANOVA the accuracy (mean of the correct responses, range: 0–1) of egocentric and allocentric categorical judgments was analyzed. The Bonferroni test was used to analyze post hoc effects. The magnitude of effect sizes was expressed by η_p^2.

4.2.1. Absolute metric error (coordinate judgments)

Results showed a main effect of FoR with egocentric judgments ($M = 5.61$, SD = 3.11) being more precise than allocentric ones ($M = 9.34$, SD = 4.34) ($F(1, 11) = 4.91$, $p < .05$, $\eta_p^2 = .31$).

4.2.2. Response time (coordinate judgments)

Results showed a main effect of FoR due to egocentric judgments ($M = 2.17$, SD = .41) being faster than allocentric ones ($M = 3.85$, SD = .58) ($F(1, 11) = 228.31$, $p < .001$, $\eta_p^2 = .95$).

4.2.3. Accuracy (categorical judgments)

No significant differences between egocentric and allocentric judgments.

4.2.4. Response time (categorical judgments)

Results showed a main effect of FoR due to egocentric judgments ($M = 2.37$, SD = .59) being faster than allocentric ones ($M = 3.98$, SD = .76): $F(1, 11) = 47.45$, $p < .001$, $\eta_p^2 = .83$).

4.2.5. Discussion

Results of the control experiment 1 showed the same pattern of data of Experiment 1 with 3D objects and 5 s of delay. This suggested that the advantage of egocentric judgments over allocentric ones was not due to the stability of the egocentric reference frame. However, we also decided to be sure that it was not due to the variability of the allocentric target. Therefore, we carried out a second control experiment in which the allocentric frame was made stable as the egocentric one by adding an external landmark.

5. Control experiment 2

To verify if the variability of allocentric reference frame influenced the pattern of data emerging from the main experiments, we decided to use a stable allocentric landmark. In this experiment participants learned the same spatial configurations of Experiment 1, but they were asked to give all the allocentric judgments with respect to an external object. If the disadvantage of allocentric judgments was due to the variability of the allocentric frame of reference, the use of a stable allocentric frame of reference was supposed to make allocentric coordinate judgments as accurate and fast as egocentric coordinate ones.

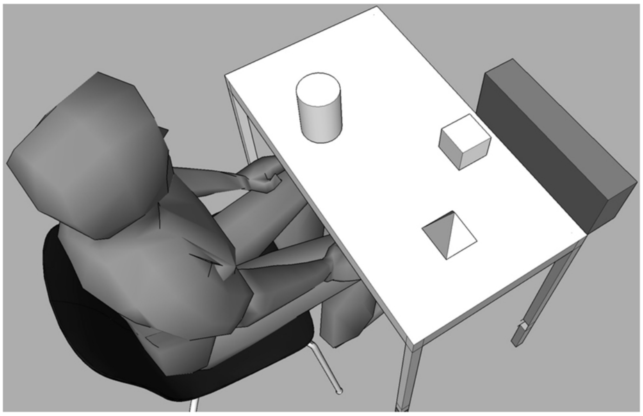

Fig. 8. The figure depicts the setting of the control Experiment 2. The experimental setting (i.e. desk, objects, triads) was the same as represented in Fig. 1a and b with the only exception of a black plastic box (length: 25 cm; height: 15 cm) posited on the side of the desk opposite to the participant. For half of the trials the black box was posited on the right side of the desk (as shown in the figure), whereas for the other half the box was on the left side of the desk.

5.1. Materials and methods

5.1.1. Participants

Twelve university students participated in the experiment in exchange for course credit or a small amount of money (6 men and 6 women, mean age = 23, SD = 2.45; range: 20–28). All participants were right handed and had a normal or corrected to normal vision.

5.1.2. Setting, stimuli and procedure

Participants were submitted to the same experimental procedure of Experiment 1 (i.e. 3D object and 5 s delay) and they were presented with the same triads of objects. The difference was that in this control experiment a black plastic box (length: 25 cm; height: 15 cm) was posited on the side of the desk opposite to the participant (see Fig. 8) and all the allocentric judgments were given with respect to the black box and not with respect to one of the 3D objects. Therefore, participants were asked to give four kinds of spatial judgments: egocentric–coordinate (where was the object closest\farthest from you?); egocentric–categorical (where was the Object X with respect to you? Right or left?); allocentric–coordinate (where was the object closest\farthest to the black box?); allocentric–categorical (where was the object X with respect to the center of the black box? Right or left?). In order to adapt the new setting with the existing configurations, half allocentric judgments were given with the black box posited on the right side of the desk, the other half with the black box on the left side of the desk. This also ensured that the target object in the allocentric categorical judgments was always on the opposite side with respect to the egocentric categorical judgments (e.g. as can be seen in Fig. 8, the cube is on the right side with respect to the participant and on the left side of the black box).

The same dependent variables of Experiment 1 were considered. The only diference was that in the allocentric categorical judgments of this control experiment participants were requested to indicate the right or the left side of the black box.

5.2. Results

Data analysis procedure was the same as Control Experiment 1.

5.2.1. Absolute metric error (coordinate judgments)

Results showed a main effect of FoR with egocentric judgments (M = 3.62, SD = 2.11) being more precise than allocentric ones (M = 7.92, SD = 4.40) (F(1, 11) = 10.96, p < .005, $\eta_p^2 = .50$).

5.2.2. Response time (coordinate judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 2.34, SD = .50) being faster than allocentric ones (M = 3.93, SD = .92) (F(1, 11) = 50.10, p < .001, $\eta_p^2 = .82$).

5.2.3. Accuracy (categorical judgments)

No significant differences between egocentric and allocentric judgments.

5.2.4. Response time (categorical judgments)

Results showed a main effect of FoR due to egocentric judgments (M = 3.31, SD = .56) being faster than allocentric ones (M = 4.00, SD = .77): F(1, 11) = 8.25, p < .05, $\eta_p^2 = .43$).

5.2.5. Discussion

Results of the second control experiment showed the same pattern of data of Experiment 1 with 3D objects and 5 s of delay. This suggested that the advantage of egocentric judgments over the allocentric ones was not due to the variability of the allocentric reference frame.

6. General discussions

The main aim of this study was to explore how people mentally represent spatial information about configurations of objects on a desk in order to guide a reaching movement toward a target position. To this aim, we combined two fundamental components of the human visuo-spatial system that is egocentric and allocentric frames of reference and coordinate and categorical spatial relations and verified if the way they combine was modulated by the temporal parameters of the response and the characteristics of the stimuli. Participants in this study learned the position of triads of objects (Experiment 1) and images (Experiment 2), afterwards they were asked to reach and touch with the index finger a position on the desk according to four kinds of instructions: egocentric coordinate (where was the object closest\farthest from you?), allocentric coordinate (where was the object closest\farthest to another one?), egocentric categorical (where was the object X with respect to you? Right or Left?), and allocentric categorical (where was the object X with respect to the object Y? Right or Left?). In Experiment 1, a group of participants saw 3D geometrical objects and gave spatial judgments immediately after stimuli had been removed, whereas another group of participants gave the same spatial judgments 5 s later stimuli had been removed. Instead, in Experiment 2, a group of participants saw 2D geometrical images and gave spatial judgments immediately after, whereas another group 5 s later stimuli had been removed. In general, results showed that coordinate judgments were more precise and faster when made with respect to an egocentric rather than an allocentric frame of reference and this was independent from the kind of stimuli used and from the temporal parameters of the response. We argue that this egocentric advantage was mainly caused by the purpose of the task. Indeed, participants were required to encode spatial information because they had to accurately indicate a position in reaching space, and the format more suitable to represent spatial information to reach this aim is the egocentric one [13]. It is important to highlight that we are not saying that participants exclusively used egocentric coordinate representations for guiding the movement, because we know from the literature that also allocentric information can cooperate with the egocentric ones to accomplish the motor task [26]. Instead, we suggest that the characteristics of the task could have favored the encoding of spatial information in egocentric rather than allocentric terms, not excluding the possibility of an allocentric information contribution to guide the movement. Moreover, the pattern of results emerging from the two control experiments rules out the possibility that the egocentric advantage could be due to the stability of the egocentric frame throughout the experiment (i.e. participants remained seated in the same place during the 24 spatial judgments) or to the variability of the allocentric one (i.e. participants did not know in advance what was the allocentric reference). Indeed, even though the control experiments had a different procedure with respect to that of the main experiments, they showed the same pattern of data.

As regards categorical spatial relations, the advantage of egocentric judgments over allocentric ones appeared only when 3D stimuli were presented and an immediate response was required. This indicates that when the task is strongly action-oriented because it requires an immediate motor response toward the position occupied by a manipulable object, then the egocentric advantage over allocentric judgment also appears for categorical spatial relations, even if the latter are thought to be more closely linked to recognition tasks and to allocentric representations. On the contrary, when 2D non-manipulable stimuli and a delayed response were used no difference appeared between egocentric and allocentric categorical judgments. These results suggest that when the visuo-perceptual characteristics of the task are stressed and when the action is memory based, allocentric and categorical spatial representations improves. Finally, for both coordinate and categorical spatial relations the presence of a 5 s delay improved allocentric judgments.

At this point it is important to discuss the implications of the evidence collected through this study with respect to the background model that inspired the research: the "double visual stream hypothesis" or "perception-action model" proposed by Milner and Goodale [13]. In brief, this model suggests that the reason why the visual processes underlying visual perception are separate from those mediating the visual control of action lies in the differences in the computational requirements of vision-for-perception on the one hand and vision-for-action on the other [15]. The vision-for-perception stream would give rise to perceptual representations of the outside world that use a scene-based frame of reference, which encodes the size, orientation and location of objects relative to each other. By contrast, vision-for-action stream needs to reflect the real metrics of the world with respect to the body. Over recent years, however, this strong division of labor has received increasing criticisms suggesting an alternative view emphasizing the integration of information across multiple visual modules and brain areas (for a review [49]; but see also Ref. [50]). The aim of this study was not to verify the reliability of Milner and Goodale's model, however our results seem to be partially compatible with that model. For example, participants were more accurate and faster in indicating egocentric locations rather than allocentric ones, and the presence of a 5 s delay improved allocentric representations. Instead, incompatible results are: (a) egocentric representations are not transient as suggested by Milner and Goodale, because they can last at least more than 5 s [24]; (b) the advantage of an egocentric representation over an allocentric one depends on the kind of spatial relations required. We have shown that an egocentric advantage is always present with coordinate spatial relations, but not with the categorical ones, and this is true for both immediate and delayed conditions. According to Milner and Goodale, a contribution of allocentric representations to the movement only appears when the response is delayed with respect to the stimuli presentation. Instead, we have shown that immediate pointing movement can be easily guided by an allocentric categorical representation but only when the positions of 2D non-manipulable figures are encoded. As a matter of fact, this result supports evidence found by Carey et al. [51], who showed that the patient D.F. with a bilateral lesion to the ventral stream was still able to perform movements according to allocentric representations but only if the kind of spatial relation was categorical and not coordinate (see also Ref. [52]).

We agree with Westwood and Goodale [53] that the way information is used and processed in the visual brain is shaped by the behavioral task, but we also think that egocentric and allocentric encoding cannot be encapsulated within a strict division of the labor of the dorsal and the ventral streams respectively. Our data show that the emergence of a spatial representation rather than another not only depends on the temporal parameters of the response or on characteristics of the stimuli, but also on the kind of spatial relations computed. Therefore, a visuo-perceptual task can be easily solved also with respect to an egocentric frame if categorical relations are used [6,20] and a visuo-motor task can be executed with a high reliability by using allocentric and categorical spatial relations. This reasoning brings us to discuss the possible relationship between frames of reference and spatial relations.

In 2003, Jager and Postma [54] proposed two hypotheses regarding the relationship between egocentric/allocentric frames of reference and categorical/coordinate spatial relations: the interaction and the independence hypotheses. The *interaction hypothesis* states that allocentric processing "more or less equates" categorical coding of spatial relations, whereas egocentric processing is closely linked to coordinate coding. Therefore, categorical spatial representations should be favored when an allocentric frame is used, whereas coordinate spatial relations processing should benefit from an egocentric anchoring. Notice that the interaction hypothesis is based on the functional similarity between FoR and SR emerging from Milner and Goodale's and Kosslyn's suggestions. Instead, the *independence hypothesis* states that frames of reference and spatial relations are distinct spatial dimensions that can be fully combined without preference for a particular kind of association. In our previous works, we verified these hypotheses and we suggested that frames of reference and spatial relations represent independent components whose interaction is modulated by the characteristics of the task at hand [6]. Results from the current study seem to corroborate this hypothesis by showing that some conditions can favor the association between functionally similar components. For example, an immediate motor response toward manipulable stimuli favors egocentric coordinate representations, whereas a visuo-perceptual task [6] with non manipulable stimuli and a delayed answer can favor the association between allocentric and categorical components. However, these associations are not independent of the task at hand as it is suggested by the interaction hypothesis. Instead, it seems that the emerging of a particular spatial representation can depend on the purpose of the task, the characteristics of the stimuli, the temporal parameters of the response and by the kind of spatial relations encoded.

From a neurofunctional perspective, since frames of reference and spatial relations have always been studied separately, it is difficult to hypothesize the neural networks supporting the four kinds of spatial representations emerging from the combination of FoR and SR. Data from neuroscience reveal that distinct but also partially overlapping brain areas support egocentric and allocentric encoding of spatial information. Overall a fronto-parietal network subtends egocentric spatial processing, whereas a subset of these regions associated with some ventral areas and hippocampal formation subtends allocentric spatial processing [35,37,38,55,56]. Instead, as regards categorical and coordinate spatial relations, some fMRI studies have suggested that the coordinate encoding engages both temporal and parietal areas, whereas categorical encoding activates a fronto-parietal network [57]. Besides, they have been found to be differently lateralized: coordinate encoding shows more right-sided activations, whereas neural correlates of categorical encoding are more left-sided [58–61]. On the basis of this evidence, Baumann and Mattingley [57] suggest that an allocentric–coordinate task should be entirely hippocampal dependent, whereas an egocentric–categorical task would be solely dependent on the parietal cortex. On the other hand, allocentric-categorical and egocentric–coordinate tasks should rely on both the hippocampus and the parietal cortex.

Future experiments will be necessary to test these neurofunctional predictions and to provide a more mechanistic understanding of the dorsal and ventral streams in spatial relation coding and reference frame processing.

6.1. Conclusions

In sum, evidence from this study supports the idea that egocentric/allocentric frames of reference and the categorical/coordinate spatial relations are different components whose combination seems likely to reflect a flexible, complex, and interactive organization that is modulated by the characteristics of the spatial task at hand.

Acknowledgments

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