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Motor imagery and engagement favour spatial reasoning

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Abstract

Based on the assumption that spatial reasoning relies on the construction of mental models of the states of affairs described in the premises, and on evidence that sensory-motor imagery can enhance cognitive abilities, we hypothesised that imagining moving the objects mentioned in the premises to the specific spatial locations should favour spatial reasoning. The results of Experiment 1 confirmed the prediction: when participants imagined moving the objects mentioned in the premises (*dynamic-engagement condition*), they drew accurate inferences faster compared with participants who merely read the premises (*static-non-engagement condition*). Experiment 2 was in part a replication of Experiment 1 but included two additional experimental conditions to control for possible effects of self-engagement in reasoning: in one condition, participants imagined that someone else was moving the objects (*dynamic-non-engagement condition*), and in the other condition, participants imagined that they were observing the objects (*static-engagement condition*). The results revealed an interaction between motor imagery and engagement in decreasing response times to spatial problems. We discuss the practical implications of the current results.

Keywords Spatial reasoning · Mental models · Motor imagery · Engagement

Introduction

Thought is based on mental representations that, as a growing body of evidence shows, cannot be understood as a "system of free and floating symbols" (Dijkstra & Zwaan, 2014), but rather as representations with sensory and motor components (Barsalou, 2008). The assumptions of the mental model theory (Johnson-Laird, 1983, 2006), our theoretical framework, are consistent with this view. The theory is a semantic theory of reasoning and therefore assumes that reasoning does not depend on syntactic operations but on iconic mental representations of the content of premises whose nature is spatial, the so-called "mental models". Consider, for example, the premise "The book is to the left of the screwdriver"; the theory assumes that individuals construct a model of the possibilities in which there is a book and a screwdriver, and this model reproduces the spatial relation between the two objects mentioned in the premise:

book	screwdriver

For convenience, we can use words to denote the elements in the model that represent the entities mentioned in the premises (i.e., a book and a screwdriver), but mental model theory claims that models are iconic as much as possible. Further, models can be updated with new information. For example, if a second premise states that "The dice is to the left of the book", we update the model as follows:

dice	book	screwdriver

The integrated model of the premises yields the conclusions "The dice is to the left of the screwdriver" or "The screwdriver is to the right of the dice".

Evidence that deductive reasoning relies on spatial representations and, at least in part, on sensorimotor activations, comes from brain imaging studies that found a main activation of brain areas involved in the representation of space, sensory integration, and movement while individuals are reasoning (Knauff et al., 2003). This evidence is at odds with syntactic theories of reasoning, which mainly predict activation of language areas (see, e.g., Brain & O'Brien,

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1998). One functional magnetic resonance imaging (fMRI) study examined activation of cortical areas as participants reasoned from relational and conditional premises, and indeed found activation of an occipitoparietal-frontal network that includes portions of the prefrontal cortex (Brodmann's area (BA) 6, 9) and the cingulate gyrus (BA 32), a network known to be involved in spatial perception and spatial working memory (Knauff et al., 2002). In addition, a meta-analysis of neuroimaging studies found that the inferior parietal lobe (BA 40), the medial frontal gyrus (BA 6 specifically), and the inferior frontal gyrus (BA 45,46) all play key roles in reasoning (Wang et al., 2020). These findings, along with evidence that both frontal areas and the inferior parietal lobe involved in reasoning exhibit mirror properties (e.g., Buccino et al., 2004; Chong et al., 2008), suggest that reasoning "may be closely related to the activation of logically related experiences, which may indicate that human deductive reasoning is at least partially derived from experience/schema/mental models" (Wang et al., 2020; pp.7-8).

It is also known that deductive reasoning strongly depends on the capacity of working memory. The greater the capacity of working memory, the more reasoning benefits. And, indeed, there is a strong correlation between working memory capacity and reasoning ability (see, e.g., Kyllonen & Christal, 1990; Süß et al., 2002). Within a mental model perspective, mental models must be kept active in working memory so that they can be updated with the information provided by all the premises of a reasoning problem (Johnson-Laird, 1983, Johnson-Laird, 1994). The load on working memory is greater when the premises support the construction of multiple models compared to one model because all of them must be kept active in order to find out whether there exists a conclusion consistent with all of them (see, e.g., Byrne & Johnson-Laird, 1989). For instance, the premises "A left of B", "C right of A", "X in front of A" and "Y in front of C" lead to the following models:

A	B	C	A	C	B
X		Y	X	Y	

These models are clearly different from each other. However, with respect to the question "what is the spatial relation between X and Y?", both models support the same conclusion, that is, "X is to the left of Y". Therefore, this kind of problem is called a multiple-model problem with a valid conclusion. There is also a different type of multiple-model problem. Consider the premises "A left of B", "C right of A", "X in front of B" and "Y in front of C" lead to the following models:

A	B	C	A	C	B
	X	Y		Y	X

With respect to the question "what is the spatial relation between X and Y?", the models support a different conclusion. Therefore, this type of problem is called a multiple-model problem with no valid conclusion and is considered the most difficult: reasoners must not only construct multiple models, but also derive a conclusion that cannot be read directly from the two models constructed, i.e., there is no valid conclusion. In the case of multiple models with a valid conclusion, the two constructed models instead support the same conclusion. Even if one constructs only one model, the reasoner will still provide the correct conclusion.

The assumption of a main involvement of working memory in reasoning by mental models was tested in a study in which participants indicated which inferences from a set of syllogistic premises were valid, and the demands on working memory were varied by manipulating the number of mental models consistent with the premises (Copeland & Radvansky, 2004). Eighty-six percent of participants drew the valid inference when the premises allowed only one mental model to be generated. This number dropped to 39% when two mental models were possible and to 31% when three mental models were possible. A study conducted within a developmental perspective found similar results (Bara et al., 2000). Participants – children, adolescents, and adults – drew their own inferences from syllogistic, propositional, and relational premises, and working memory demands were varied by manipulating the number of mental models that matched the premises (one model and multiple models). In addition, the basic abilities involved in constructing mental models, such as working memory capacity, were examined. As the results showed, one-model problems were easier than multiple-model problems for all types of deductive problems, and participants' working memory capacity correlated significantly with their accuracy in deductive reasoning. Oberauer et al. (2006) also show that the capacity of working memory affects the likelihood of creating an adequate mental model of the presented spatial arrangement.

From these findings, it follows that variables that can promote memory performance should also promote reasoning performance. The literature on memory suggests that mental imagery is a good strategy for improving memory performance. Mental imagery can be defined broadly as a simulation of perceptual experience that evokes a perceptual experience without the presence of a real external stimulus. There are several studies that indicate a positive influence of mental imagery on various types of memory performance. For example, memory for verbal material improves significantly when participants are asked to mentally imagine the content being learned during encoding (see Pressley & Brewster, 1990; Paivio, 1971). Imagery instructions also appear to have positive effects in recognition tasks (e.g., Oliver et al., 2016) and in reducing false memories in the DRM paradigm (e.g., Foley, 2012; Foley et al., 2006, 2012).

The general definition of mental imagery as a simulation of perceptual experience encompasses different types of mental imagery depending on which perceptual modality is involved. Thus, for example, visual mental imagery consists of visualising details of an object (e.g., shape and colour) and depends on activation of the same cortical areas involved in visual perception (e.g., Dijkstra et al., 2017). In contrast, motor imagery refers to the ability to internally reproduce movements and physical activities with objects without any overt motor activity. Like visual imagery, motor imagery involves the same brain areas (i.e., premotor cortex and primary motor cortex) that are responsible for planning and executing movements (Decety, 1996), and it also leads to activation of the muscles of the limbs involved in the imagined action. Interestingly, the temporal duration of imagining a movement correlates with the actual duration required to execute the same movement, suggesting a type of motor simulation (Decety, 1996).

It is reasonable that motor imagery should have a better impact on reasoning processes compared to visual imagery, for at least two reasons. First, several studies have shown that too vivid visual representations can actually impede reasoning, by making salient aspects of the states of affairs described by the premises that are irrelevant to the reasoning task (Knauff & Johnson-Laird, 2002; Knauff & May, 2006). Consistent with these findings, neuroimaging studies of deductive reasoning have shown that visual regions do not play a crucial role in reasoning (Knauff et al., 2003). Second, studies of memory capacity suggest a "memory efficiency gradient running from low-embodiment strategies [...] to high-embodiment strategies (i.e., rich simulation in the sensory and motor systems involved in interaction with the objects)" (Marre et al., 2021; p.1396). They compared the effect of a simple visual imagery task with a motor imagery task on memory for words. There were four experimental conditions: a mental rehearsal condition involving no mental imagery, a visual imagery condition involving the imagination of visual features of the objects, and two embodied motor imagery conditions (third–first person). The study thus compared different encoding strategies lying on a continuum ranging from low-embodiment to high-embodiment. The results showed that having both visual and motor imagery proved to be the most effective strategy: "Adding the simulation of motor characteristics to purely visual imagery improved its memory benefits" (ib., p.1401). Further, there is evidence that memory benefits from motor imagery in terms of both long-term and short-term memory. Indeed, the number of correct and incorrect responses was analysed for both delayed recall (2 days later) and immediate recall. Crucially, they found that high embodiment strategies had a positive effect on both delayed and immediate recall, thereby suggesting that motor imagination plays a role in both types of memory processes (Marre et al., 2021). Given the role of short-term memory in reasoning tasks, it is reasonable to predict a similar effect of motor imagery in spatial reasoning tasks.

Behavioural (Louwerse et al., 2015) and neuroimaging (Kiefer & Pulvermüller, 2012) studies have shown that deep discourse comprehension involves reactivation of sensorimotor experiences, not only when individuals process words and sentences, but also during discourse comprehension (e.g., Nijhof & Willems, 2015). There are several lines of evidence that description of actions with objects lead to activation of motor areas. Using fMRI, Willems et al. (2010) found that right-handers preferentially activated left premotor cortex during lexical decisions on manual-action verbs (compared with nonmanual-action verbs), whereas left-handers preferentially activated right premotor areas. Similarly, participants in an rTMS study were asked to judge as quickly as possible whether a set of stimuli consisted of a real English verb (e.g., to pour) or a meaningless pseudo-verb (e.g., to prouker) (Willems et al., 2011). Real verbs referred either to a manual action, typically performed with the dominant hand (e.g., to pour) or to a non-manual action (e.g., to wander). If semantic processing consists of using the motor areas of the brain involved in performing the action denoted by the verb, then only the left premotor hand area (and not the right premotor hand area controlling the nondominant hand) would be involved in processing the meaning of action verbs that refer to manual actions (and not to nonmanual actions). These predictions have been confirmed: inhibition of left premotor cortex (but not right premotor cortex) affected participants' reaction times when responding to manual verbs (but not to nonmanual verbs). In other words, impairment of left premotor cortex functions affected how quickly participants responded to linguistic stimuli. These results provide evidence that somatotopic motor activity is involved in processing the semantic meaning of action verbs. Consistent with this assumption, the results of studies on the memory of action sentences have shown that a posture that restricts the readiness to act on an object has a detrimental effect. In one study, participants' task was to memorize sentences containing action verbs (e.g., "To take a cup") or attention verbs (e.g., "To see a cup") (Dutriaux et al., 2019). When asked to adopt a posture that restricted their readiness to act during encoding (i.e., interfering posture with arms and hands behind the back), they showed a decrease in recall of objects associated with action verbs but not for objects associated with attention verbs.

The main assumption of the present investigation is that increased motor activation in reasoners, based on motor information in the premises, should benefit their reasoning ability in spatial problems by enhancing memory for mental models. Since our goal was to explore the role of motor activation in reasoning from premises rather than in performing actions described by the premises, it was crucial to figure out how to increase motor activation without requiring overt movements of the objects mentioned in the premises. We hypothesised that instructions that focus on motion should be a good solution because several studies have shown that people rely on a sensorimotor simulation of action when understanding an action-related sentence (see, for a review, Fischer & Zwaan, 2008), and that reading action words that refer to facial, arm, or leg movements triggers somatotopic activation in readers' premotor areas (e.g., Hauk et al., 2004). Participants in the present study were asked to imagine the objects mentioned in the spatial premises in all experimental conditions, and it is well known that imagining objects can also activate motor regions (Kosslyn et al., 2001), as can understanding action verbs (Willems et al., 2010). With this in mind, we hypothesise that dynamic instructions such as "Put the book to the right of the screwdriver" will elicit greater motor activation compared to static instructions such as "The book is to the right of the screwdriver". Hence Experiment 1 tested the following hypothesis:

> *Hypothesis 1:* Because reasoning ability depends on memory capacity and motor imagery enhances memory more than other cognitive strategies, participants should be more accurate and faster in the dynamic condition than in the static condition.

However, the beneficial effect of motor imagery in Experiment 1 could be based on two different mechanisms. On the one hand, motor imagery promotes the re-enactment of motor (and potentially kinaesthetic and tactile) experiences (Marre et al., 2021), and this could play a central role in reasoning tasks that rely heavily on modalities other than visual. On the other hand, motor imagery may also lead to higher levels of self-involvement in the task, which is known to be a crucial factor in memory and learning (e.g., Rogers, 1977). To disentangle these two possible mechanisms, in Experiment 2 we directly manipulated both factors and developed four experimental conditions (dynamic engagement, dynamic-non-engagement, static engagement, static-non-engagement):

> *Hypothesis 2:* If only self-involvement plays a role in speeding reaction times, we should find a main effect of self-involvement (i.e., faster reaction times under both dynamic and static engagement conditions). If only motor involvement plays a role in the acceleration of reaction times, we should find a main effect of motor imagery (i.e., faster reaction times in both dynamic conditions). If both factors play distinct roles, we should find two main effects, and if both factors play a role and interact, we should also find a significant interaction.

Experiment 1: Motor imagery favours reasoning

The experiment tested the prediction that spatial reasoning is favoured when individuals imagine moving the objects mentioned in the premises to the specific spatial locations as compared to when they simply read about the objects' spatial locations. Participants in the experiment faced a series of spatial problems on a computer screen. For each problem, their task was to decide whether an object was either to the left or to the right of another object.

More specifically, the participants encountered a series of spatial problems, each describing the spatial configuration of five objects. Their task was to state the spatial relation between two of them. An example is the problem:

(1) The book is to the right of the screwdriver
The screwdriver is to the left of the felt-tip pen
The dice is in front of the felt-tip pen
The USB is in front of the screwdriver
Where is the dice with respect to the USB?

Since human beings build mental representations by exploiting their sensorimotor resources, we assumed that presenting the very same problem with the invitation to imagine moving the objects in the relevant spatial positions rather than just describing the objects' position should facilitate reasoning. With the aim of testing this prediction, we used parallel versions of the standard spatial problems; the following is the parallel version of the problem above:

(2) Put the book to the right of the screwdriver
Put the screwdriver to the left of the felt-tip pen
Put the dice in front of the felt-tip pen
Put the USB in front of the screwdriver
Where is the dice with respect to the USB?

Method

Participants

The participants of the experiment were 88 students (63 female, 25 males, mean age 26.02 years, SD = 7.38) from the University of Torino. They voluntary participated in the experiment after giving informed consent in exchange of course credits. The sample size was determined through a simulation-based power analyses (Kumle et al., 2021) using the reaction times data obtained in a pilot study run on 34 participants. Based on the mixed-effect model including the same fixed and random factors of those reported in the current experiment, 1,000 new data sets, each containing n participants (65,75,85,95) were simulated using the mixed-power() function in R. For n = 85 simulated participants, we estimated a statistical power of .811; that is for 811 out of 1,000 simulations, the model detected a significant effect. Therefore, we tested 88 participants. This experiment and Experiment 2 were approved by the Ethics Committee of the University of Turin.

Material

The participants were presented with problems describing the spatial configuration of five objects: four one-model problems and four multiple-model problems with a valid conclusion, as detailed in Appendix 1.

One-model problems were based on the following structure:

A	B	C
X		Y

Premises 1 and 2 always describe the relations between A and B and between B and C, respectively.

We created four problems by changing the description of the relation between the terms in premises 1 and 2 and by balancing the occurrence of the descriptions of the relations between X and A and between Y and C in premises 3 and 4. The direction of the question (i.e., where X is in relation to Y or where Y is in relation to X) was balanced over all problems.

Multiple-model problems were based on the following structures:

A	B	C	A	C	B
X		Y	X	Y	

And the following two basic types:

- A left of B; C right of A; X in front of A; Y in front of C; relation between X and Y?
- B right of A; A left of C; X in front of A; Y in front of C; relation between X and Y?

Again, we obtained the two variations by switching the order of mentioning of X and Y in premises 3 and 4 (Y in front of C; X in front of A).

For each of the eight problems, we also created a parallel dynamic version by converting each description of the relative spatial location of two objects (e.g., The book is to the right of the screwdriver) into an imperative assertion that specifies putting the two objects in that spatial location (i.e., Put the book to the right of the screwdriver).

Procedure

We created two experimental conditions: participants in the static non-engagement condition encountered the standard versions of the eight problems, and participants in the dynamic engagement condition encountered the parallel dynamic versions. Half of the participants were randomly assigned to the static condition and the other half to the dynamic condition.

The premises were presented via a computer screen, one at a time, each lasting 8 s. After the presentation of the fifth premise, a question about the relative position of two of the named objects appeared on the screen. The participant's task was to press the "B" key or the "N" key on a QWERTY computer keyboard to answer "left" or "right" depending on whether they inferred that one of the two objects was to the left or to the right of the other one. The instructions were as follows:

> Thank you for your participation. In this experiment you will have to solve some reasoning problems. Each one consists of four statements that appear on the screen one after the other for 8 s. After the presentation of the last statement, a question will appear that you must answer "left" or "right". Press B to answer left, press N to answer right. Keep two fingers of the same hand resting on the two keys throughout the experiment.

In the static non-engagement condition the instructions continued as follows:

> To solve the problems, we ask you to imagine where some objects are placed.

In the dynamic engagement condition the instructions continued as follows:

> To solve the problems, we ask you to imagine yourself while placing objects in certain positions.

Results

Table 1 shows the mean response times of correct responses in each experimental condition. We used a 2 × 2 mixed experimental design, with type of instruction (static versus dynamic) as the between variable and number of models (one model versus two models) as the within variable.

Following the guidelines in the psycholinguistic literature (Barr et al., 2013), we started from the theoretical full model (by including the maximal structure of random effects supported by the design) and then applied to this model the *step* function in the lmerTest package (Kuznetsova et al., 2017) to find the final mixed model in which the factors with non-significant effects were removed. This function performs backward elimination of non-significant effects (both random and fixed). Appendix 2 gives the final model found by the step function in the package lmerTest. The final model revealed a significant effect of Instruction ($\beta = .08$, SE = .04, t = 2.23, $p < .05$) on log-transformed reaction times. Participants were faster in correctly evaluating problems in the dynamic instruction condition (a mean of 4,500 ms, SD = 1,924 ms) compared to the static instruction condition (a mean of 6,255 ms, SD = 4,381 ms).

Table 1 Mean response times (and standard deviations) to problems presented with static and dynamic instruction in Experiment 1

Condition	One-model problems	Multiple-models problems	Mean
Static instruction	6,103 (SD = 4,483)	6,408 (SD = 6,075)	6,255 (SD = 4,381)
Dynamic instruction	4,342 (SD = 2,713)	4,648 (SD = 1,740)	4,500 (SD = 1,940)

Table 2 Mean accuracy (and standard deviations) for problems presented with static and dynamic instruction in Experiment 1

Condition	One-model problems	Multiple-models problems	Mean
Static instruction	0.68 (SD = .24)	0.63 (SD = .25)	0.66 (SD = .19)
Dynamic instruction	0.66 (SD = .25)	0.64 (SD = .28)	0.65 (SD = .22)

Table 2 illustrates the accuracy rates on problems as a function of the type of instruction. Using a binomial mixed-effect logistic regression model (model code in Appendix 2) implemented with the *glmer* () function for the dependent variable (binary outcome, 0 for incorrect and 1 for correct responses), we found no significant effect of Instruction on accuracy rates ($\beta = 0.15$, SE = 0.27, $z = 0.56$, p =.58, odds ratio: 0.86, 95% CI [0.51, 1.46]), nor a significant effect of Number of models ($\beta = 0.27$, SE = 0.24, $z = 1.15$, p =.25, odds ratio: 0.76, 95% CI [0.48, 1.21]), nor a significant interaction ($\beta = 0.19$, SE = 0.33, $z = 0.57$, p =.57, odds ratio: 1.21, 95% CI [0.63, 2.31]). Thus, participants' accuracy on problems presented with dynamic instructions was not higher than on problems presented with static instructions.

Overall, the results of Experiment 1 confirmed the prediction that imagining moving the objects mentioned in the premises favours spatial reasoning, which was reflected in faster response times with the dynamic instruction, and they strengthen the assumption that motor imagery plays an important role in reasoning. An unexpected result was that both accuracy and response times for one-model and multiple-model problems were comparable. We will come back to this observation in the *General discussion*. There is, however, another potential problem with Experiment 1: the imagery-manipulation might have made the task more engaging for the participants. Therefore, we designed Experiment 2 to disentangle the role of motor imagery from the role of engagement in the effect found in Experiment 1. For consistency, we used the same set of problems, but we did not predict further differences in performance with one-model and multiple-model problems.

Experiment 2: Disentangling the role of motor imagery and engagement in reasoning

Experiment 1 nicely demonstrated an effect of motor imagery on reasoning. However, the manipulation of the instructions not only manipulated motor imagery, but it might have also manipulated the engagement of the participants. Indeed, the use of dynamic reasoning tasks compared to static tasks might favour reasoning because participants are more active and engaged, a component known to facilitate memory processes.

There is evidence that active learning, defined as "instructional activities involving students in doing things and thinking about what they are doing" (Bonwell & Eison, 1991), helps to learn more effectively than classic approaches in which learners are merely passive recipients of what is said by someone else (the effect is robust; for a meta-analysis, see Freeman et al., 2014). The "overarching" definition of active learning can include a variety of activities, ranging from the very simple (e.g., repeating what has been read) to the more complex (e.g., summarising what has been read). One effective method for promoting active learning is so-called "student-centred instruction", a teaching approach in which students influence the content, material, and pace of learning. "Student-centred" means that the learner participates to some degree in the procedures required to access learning, rather than merely observing the role of the teacher, as commonly defined in contrast to "teacher-centred" (Pedersen & Liu, 2003). In this learning strategy, the attention is on what the students do, and the students' behaviour is the determining factor for the whole process. This approach to learning results in (1) better knowledge retention, (2) deeper comprehension, (3) increased motivation, and (4) generally more positive attitudes toward the learning process (see Michael, 2006). Although there are several ways to implement this strategy, they all have in common that they place the learner at the centre of the learning process. This approach includes, among other things, engaging students in simulations and role-playing (Michael & Modell, 2003). Thus, the process of building mental models and consciously and intentionally testing them can be fostered by explicitly asking participants to engage in the simulative process that underlies the elaboration of premises.

Experiment 2 was designed to disentangle the possible effects of motor imagery and engagement in spatial reasoning. The task of participants in Experiment 2 was the same as in Experiment 1: they encountered spatial problems on a computer screen and were asked to infer whether a given object was either to the left or the right of another. To disentangle the role of the motor component "per se" from the role of engagement in spatial reasoning, we added a condition in which the motor component was present, and engagement was absent: participants were asked to imagine someone else moving the objects. In this *dynamic-non-engagement condition*, participants received the following parallel version of dynamic problem of Experiment 1:

(3) Andrea puts the book to the right of the screwdriver
Andrea puts the screwdriver to the left of the felt-tip pen
Andrea puts the dice in front of the felt-tip pen
Andrea puts the USB in front of the screwdriver
Where is the dice with respect to the USB?

Further, in the second experiment we added an engagement condition without a motor component: Participants were asked to imagine themselves observing objects. In this *static-engagement condition*, participants received the following parallel version of the problem above:

> You see the book to the right of the screwdriver
> You see the screwdriver to the left of the felt-tip pen
> You see the dice in front of the felt-tip pen
> You see the USB in front of the screwdriver
> Where is the dice with respect to the USB?

Within our embodied cognition perspective, the static engagement condition helps reasoners "see" the situation described in the premises in their minds, whereas the dynamic engagement condition explicitly encourages them to reactivate sensorimotor experiences.

Method

Participants

We tested 160 adults (129 females, 31 males, mean age 23.59 years, SD = 4.53) at the University of Torino. Participation in the experiment was on a voluntary basis and in exchange for course credits, after informed consent. Roughly the same as in Experiment 1, we tested 40 participants for each experimental condition.

Materials and procedures

The material consisted of the same spatial problems used in Experiment 1. In Experiment 2, we created two additional experimental conditions: static engagement and dynamic non-engagement conditions. Participants were randomly assigned to the four conditions, resulting in a total of 40 participants in each condition. Participants were introduced to the experimental tasks with the same general instructions. The specific instructions for each experimental condition varied depending on the variable manipulated. To this end, the instructions for the static non-engagement condition differed slightly from those in Experiment 1:

> To solve the problems, we ask you to imagine objects in certain positions.

In the dynamic engagement condition the instructions continued as follows:

> To solve the problems, we ask you to imagine yourself while placing objects in certain positions.

As for the new conditions in the experiment, the specific instructions for the static engagement condition were:

> To solve the problems, we ask you to imagine yourself while seeing objects in certain positions.

And the specific instructions for the dynamic non-engagement condition were:

> To solve the problems, we ask you to imagine a person, Andrea, while moving objects in certain positions.

Results

Since the number of models did not affect participants' responses in Experiment 1, we did not consider this factor in this analysis. Further, preliminary paired t-test comparisons revealed that neither accuracy nor reaction times differed for one-model tasks and multiple model tasks as detected in Experiment 1 (t(160) = .55, $p = .58$ for accuracy; t(150) = .26, $p = .79$ for reaction times).

Table 3 shows the mean response times of correct responses in each experimental condition. We used the same mixed model approach with the lmer Test package as in Experiment 1, but without number of models as a factor. Appendix 2 gives the final model. This final model revealed a significant effect of Motor component ($\beta = .15$, SE = .05, t = 3.40, $p < .001$) on log-transformed reaction times, as well as a significant effect of Engagement component ($\beta = .18$, SE = .05, t = 4.13, $p < .001$) and a significant interaction ($\beta = .17$, SE = .06, t = 2.72, $p < .01$).

Table 4 illustrates the accuracy rates on problems as a function of the type of instruction. Using a binomial mixed-effect logistic regression model (model code in Appendix 2) implemented with the glmer () function, we found no significant effect of Motor component on accuracy rates ($\beta = 0.09$,

Table 3 Mean of response times (and standard deviations) to spatial problems as a function of instruction and engagement in Experiment 2

	Engagement	Nonengagement
Static	5,044 (SD = 1,808)	8,284 (SD = 4,362)
Dynamic	5,452 (SD = 2,249)	5,839 (SD = 2,759)

SE = 0.19, z = 0.46, *p* =.65, odds ratio: 1.09, 95% CI [0.75, 1.59]), nor a significant effect of Engagement (β = 0.17, SE = 0.19, z = .91 , *p* =.37, odds ratio: 1.19, 95% CI [0.82, 1.73]) or a significant interaction (β = 0.23, SE = 0.27, z = 0.86 , *p* =.39, odds ratio: 0.79, 95% CI [0.47, 1.35]).

General discussion

Experiment 1 tested the prediction that increased motor activation in reasoners should benefit their reasoning ability in spatial problems. The results confirmed the prediction: when participants imagined moving the objects mentioned in the premises (*dynamic-engagement condition*), they drew accurate inferences faster compared to participants who merely read the premises (*static-non-engagement condition*). Experiment 2 examined the individual contribution of motor imagery and engagement to spatial reasoning improvement by including a condition in which participants imagined that someone else was moving the objects (*dynamic-non-engagement condition*) and a condition in which they imagined that they were observing the objects (*static-engagement condition*). The results of Experiment 2, while confirming an important role of self-involvement, also provide evidence for a genuine role of motor imagery in reasoning tasks. Syntactic theories could not have predicted these results because if the mental representations underlying reasoning are abstract and primarily linguistic, low embodiment strategies should lead to the same results as high embodiment strategies. In other words, these theories cannot predict that sensorimotor elements are privileged cues for constructing mental representations needed to solve deductive tasks.

Experiments 1 and 2 yielded comparable results: participants drew more accurate inferences faster in the dynamic-engagement condition than in the static-non-engagement condition. Interestingly, Experiment 2 not only revealed a main effect of Instruction (with the dynamic conditions being faster) and of Engagement (with the engaged conditions being faster), but also a significant interaction, revealing that engagement needs to be faster more in the case of static instructions than in the case of dynamic instructions. Why that is the case cannot be determined on the basis of the current experiments. One plausible explanation is that asking participants to imagine themselves while seeing objects in certain positions (as in the static engagement condition) may have triggered automatic motor imagery. Although this explanation is consistent with other research showing automatically triggered motor imagery (Chao & Martin, 2000; Sirigu & Duhamel 2001), other studies cast doubt on it. There is research stating that only the first-person perspective leads to motor imagery with kinaesthetic feedback (e.g., Jeannerod, 1994; Mellet et al., 1998), suggesting that rapid performance in the dynamic non-engagement condition (imagining someone else moving objects) may not be caused by motor imagery. Other experimental evidence shows that motor activation is more involved in the comprehension of action verbs than in the comprehension of attention verbs: when participants were asked to learn sentences containing action verbs (e.g., “Take a cup”) and attention verbs (i.e., “See a cup”) while holding their hands in front of them (non-interfering condition) or holding them behind their backs (interfering condition), interfering body position affected recall of objects associated with action verbs but did not affect recall of objects associated with attention verbs (Dutriaux et al., 2019). These results suggest that motor activation is greater for action verbs than for attention verbs. Future studies could examine the effects of types of engagement without a motor component on spatial reasoning, and could also consider individual differences in the ability to use motor imagery (see Madan & Singhal, 2012). One possible avenue is to measure motor imagery ability, but a more promising avenue seems to be to practice motor imagery before the actual task. This might also be important because some participants might spontaneously tend to use visual imagery instead of motor imagery, as motor imagery is more demanding than visual imagery (see, e.g., de Lange et al., 2008).

The last point brings us to an important difference between our study and some other imagery studies in the field of relational reasoning. A number of studies have shown a detrimental effect of imagery, but these studies focused on visual imagery. For example, Knauff and Johnson-Laird (2002) found that simple relational reasoning problems with visual relations such as “cleaner” and “dirtier” were solved more slowly than comparable problems with visuospatial relations such as “above” and “below”. Knauff and Johnson-Laird (2002) argue that this is due to the ease of visualizing the visual relations. Consider the premise “The horse is dirtier than the cow.” This sentence is easy to visualize, but such an image could also contain irrelevant visual details. Thus, to draw a conclusion, reasoners must isolate and focus on the relevant aspects of the problems, a

Table 4 Accuracy rates (and standard deviations) in each experimental condition of Experiment 2

	Engagement	Nonengagement
Static instruction	.67 (SD = .16)	.63 (SD = .20)
Dynamic instruction	.63 (SD =.18)	.65 (SD = .21)

process that takes time. Knauff and May (2006) replicated this finding and additionally found that people who are blind from birth do not show these impedance effects because they are unable to envisage visual mental images.

As discussed in the introduction to Experiment 2, a student-centred learning strategy can lead to better knowledge retention, deeper comprehension, higher motivation, and a generally more positive attitude toward the learning process (Michael, 2006). It is important to emphasize that these benefits are not only important during online model construction – memory benefits as well. Participants are generally more likely to remember things from the past if they played an active role in selecting or creating the information (see also Cloutier & Macrae, 2008). There is even a growing literature on the role of self-involvement in memory processes, and again, there are several ways to realize this effect. A seminal study by Symons and Johnson (1997) showed that participants who were asked to memorize items describing personality traits performed better when asked to rate the extent to which these items described themselves during encoding than when asked to make the same judgements but in relation to other people (e.g., parents). Similarly, studies on action observation and recognition show that people tend to be better at recognizing their own actions than the actions of others (Knoblich & Flach, 2003). In other words, the literature has shown that recall is increased for items that have been self-manipulated or self-referenced during encoding. Given this literature and the central role of working memory in reasoning tasks (see, e.g., Barrouillet & Lecas, 1999; Oberauer et al., 2006), one could argue that engaging in premises elaboration can enhance reasoning abilities in several ways. Engaging in processing premises should facilitate the construction, maintenance and manipulation of mental models during spatial reasoning. Experiment 2 was designed to disentangle the possible effects of motor imagery and engagement during spatial reasoning.

Two unexpected results require further explanation. First, response times were generally shorter in Experiment 1 compared to Experiment 2. This is most evident for the static instruction condition, with a mean reaction time of 6255 ms in Experiment 1 and 8284 ms in Experiment 2. This unexpected difference can be explained by two small but not unimportant changes. The instructions in Experiment 2 called for "imagining where some objects are placed", whereas in Experiment 1 they called for "imagining objects in a particular position". The passive form in Experiment 2 may have slowed comprehension. Moreover, unlike the instructions for the same conditions in Experiment 1, the instructions for the static non-engagement condition and for the dynamic engagement conditions in Experiment 2 included instructions to imagine the objects in a particular position, which may also have slowed response times. These small changes were necessary to ensure a good manipulation of both engagement and motor imagery but might have slowed down some of the reasoners in Experiment 2.

Second, in both experiments, one-model and multiple-model problems were of equal difficulty. The relational reasoning literature generally shows that one-model problems are easier than multiple-model problems (e.g., Byrne & Johnson-Laird, 1989), although there are some exceptions (see, e.g., Experiment 3 in Schaeken et al., 1996). This lack of difference seems not to be caused by a remarkable low performance on the one-model problems. In our experiments the one-model problems were solved more or less at the same level as, for instance, in the classic study on spatial reasoning of Byrne and Johnson-Laird (1989), that is, between 60% and 70% correct (for similar one-model results, see e.g., Vandierendonck & De Voogt, 1996). The reason for the lack of a difference between the one-model and multiple-model problems in our study is more likely the quite good performance on the multiple-model problems, given the sequential presentation of the premises: in our experiments the performance was about 10–15% better than in Byrne and Johnson-Laird (1989) and Vandierendonck and De Voogt (1996). There is an important methodological difference between our experiments on the one hand and classical experiments on the other, which could explain the rather high number of correct multiple-model conclusions. In the latter, both valid and invalid problems are presented, whereas we presented only problems with valid conclusions. Since in relational problems the different models of the multiple-model problems yield the same conclusion, it is not necessary to construct all the models to produce a valid conclusion. However, problems with no valid conclusion can only be answered correctly if the reasoner constructs all possible models and infers that there is no informative conclusion consistent with all these models. Importantly, multiple-model and no-valid-conclusion problems have the same structure, so one cannot infer from the premises themselves that it is not necessary to construct more than one model; it is only the question that causes the difference between these two types of spatial problems. Thus, the classic mix of multiple-model and no-valid-conclusion problems probably makes it more likely that participants will construct multiple models, which thwarts solving the multiple-model problems. Future research could replicate the current study but additionally present problems with no valid conclusion to motivate reasoners to construct multiple models. According to our embodied cognition perspective, the static engagement condition might facilitate reasoners in "seeing" the situation described in the premises in their minds (a procedure similar to that in Marre et al., 2021), whereas the dynamic engagement condition explicitly encourages them to reactivate sensorimotor experiences. Consequently, especially no-valid-conclusion problems might benefit from the latter instructions. However, for the purpose of the current study, that is, an initial investigation of the effects of motor imagery and engagement in spatial reasoning, the lack of a difference between one- and multiple-model problems is not crucial.

Overall, the effects observed in the two experiments should be interpreted with caution. We must not overinterpret embodied effects in reasoning contexts. First, we found benefits only in terms of response times. These data are consistent with most studies in the literature on embodied cognition, in which effects of sensorimotor manipulations on higher cognitive processes have been found only in the form of small changes in response times (Ianì, 2022). In the area of semantic memory, for example, inhibition of modality-specific brain areas or sensorimotor pathways has been shown to produce only small changes in reaction times (see Casasanto, 2022). An important question underlying this limitation of embodied approaches is: how much of cognition is embodied in sensorimotor simulations? Indeed, most experimental studies have found effects related to the availability of a mental representation (Ianì, 2019). In other words, the effects predicted by the embodied cognition approach might be a matter of "cognitive resources": procedural elements seem to be able to change the availability of memory traces (the process), but not their content (the representation of a memory itself). In addition, future studies should examine the long-term effects of this type of manipulation.

Not only motor imagery plays a role in the processes underlying reasoning. The data from the two experiments seem to support the idea that sensorimotor simulation is only one element among others, such as self-involvement, that play a role in deductive spatial abilities. Self-engagement may play a significant role in tasks that are considered in the literature to be purely motor or not motor at all, while they may also have different levels of self-engagement. In general, the present results show the importance of separating the positive effects of self-engagement from those of motor activation on higher cognitive functions. Future studies could investigate the effects of rTMS on sensorimotor areas to observe how it affects spatial reasoning under dynamic and engaging instructions, thus disentangling the roles of motor imagination and self-engagement.

Conclusions

The two experiments in the current study on spatial reasoning show that participants who imagined moving the objects mentioned in the premises drew correct inferences faster than participants who merely read the premises. Experiment 2 also showed that participants drew correct inferences faster when they imagined themselves observing objects. These results suggest a facilitatory effect of motor imagery and engagement, consistent with an embodied cognition perspective on mental model theory, but contrary to the assumptions of syntactic theories of reasoning. Future research needs to disentangle the specific effects of motor imagery and engagement.

Appendix 1

The spatial relational problems used in the experiments.

One-model problems:

A left of B. C right of B. X in front of A. Y in front of C. Where is X with respect to Y?
A left of B. C right of B. Y in front of C. X in front of A. Where is Y with respect to X?
B right of A. B left of C. X in front of A. Y in front of C. Where is X with respect to Y?
B right of A. B left of C. Y in front of C. X in front of A. Where is Y with respect to X?

Two-model problems:

A left of B. C right of A. X in front of A. Y in front of C. Where is X with respect to Y?
A left of B. C right of A. Y in front of C. X in front of A. Where is Y with respect to X?
B right of A. A left of C. Y in front of C. X in front of A. Where is Y with respect to X?
B right of A. A left of C. X in front of A. Y in front of C. Where is X with respect to Y?

Appendix 2

Model codes for Experiments 1 and 2.

Experiment 1: Reaction times

Starting model

RT_log ~ TypeInstruction*NumberModels + (1+NumberModels|Subjects) + (1 + TypeInstruction*NumberModels|Item)

Model found

RT_log ~ TypeInstruction + (1 | Soggetto)

Experiment 1: Accuracy

Accuracy ~ TypeInstruction*NumberModels + (1 | Soggetto) + (1 |Item_Cod)

Experiment 2: Reaction times

Starting model

RT_log ~ Motor*Engagment + (1|Subjects) + (1+ Motor*Engagment|Item)

Model found

RT_log ~ Motor + Engagment + (1|Subjects) + Motor*Engagment

Experiment 2: Accuracy

Accuracy ~ Motor * Engagment + (1|Subjects) + (1 |Item_Cod)

Data Availability The data from the present experiment are publicly available at the Open Science Framework website: https://osf.io/ns2t6/

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