Acta Psychologica 157 (2015) 144–154

Contents lists available at ScienceDirect

Acta Psychologica

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

Grounded spatial belief revision

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ARTICLE INFO

Article history:
Received 22 April 2014
Received in revised form 3 November 2014
Accepted 11 February 2015
Available online 19 March 2015

PsycINFO classification codes:
2300
2340

Keywords:
Spatial cognition
Grounded cognition
Mental models
Belief revision
Spatial reasoning

ABSTRACT

Beliefs frequently undergo revisions, especially when new pieces of information are true but inconsistent with current beliefs. In previous studies, we showed that linguistic asymmetries provided by relational statements, play a crucial role in spatial belief revision. Located objects (LO) are preferably revised compared to reference objects (RO), known as the LO-principle. Here we establish a connection between spatial belief revision and grounded cognition. In three experiments, we explored whether imagined physical object properties influence which object is relocated and which remains at its initial position. Participants mentally revised beliefs about the arrangements of objects which could be envisaged as light and heavy (Experiment 1), small and large (Experiment 2), or movable and immovable (Experiment 3). The results show that intrinsic object properties are differently taken into account during spatial belief revision. *Object weight* did not alter the LO-principle (Experiment 1), whereas *object size* was found to influence which object was preferably relocated (Experiment 2). *Object movability* did not affect relocation preferences but had an effect on relocation durations (Experiment 3). The findings support the simulation hypothesis within the grounded cognition approach and create new connections between the spatial mental model theory of reasoning and the idea of grounded cognition.

1. Introduction

Imagine you have a date with a friend in a foreign city. He described to you how to get to the meeting point: “When you get off the train, you will see the kiosk to the left of you, and an ice cart to the right of you. To the left of the kiosk, I will wait for you.” This description is compatible with the following mental model:

Kiosk–I–ice cart.

Almost arriving you receive a phone call from your friend who tells you: “I made a mistake. The kiosk is to the right of the ice cart”. On which side is your friend waiting for you? In fact there are two possibilities:

I–ice cart–kiosk   Ice cart–kiosk–I .

In everyday life, we are often confronted with such problems. People describe how to find certain objects and then realize that the description is wrong (“I left your key on the kitchen table", but it is actually on the table in the living room); someone describes how to find a certain place in a foreign city and on your way, you realize that his description was wrong; your partner describes where he parked your car, but it is parked somewhere different, and so on (Bucher, Röser, Nejasmic, & Hamburger, 2014). All this has to do with the field of “belief revision”. Researchers in this field explore how people change their mind in the light of new contradicting information. The experimental studies mostly used conditional reasoning problems in which an inconsistency arises between a fact, contradicting a valid conclusion, and the conditional and categorical premises. Within this research, psychologists were able to show that belief revision is affected by many factors, including asymmetries between particular facts and general laws (Revlis, Lipkin, & Hayes, 1971), conditional and categorical premises (Dieussaert, Schaeken, De Neys, & d'Ydewalle, 2000; Elio & Pelletier, 1997; Girotto, Johnson-Laird, Legrenzi, & Sonino, 2000; Politzer & Carles, 2001; Revlin, Cate, & Rouss, 2001), major and minor premises (Politzer & Carles, 2001), and reliable and unreliable information sources (Wolf, Rieger, & Knauff, 2012).

The present work is part of our endeavor (1) to extend the cognitive research on human belief revision to the area of spatial reasoning and (2) to combine this research with the idea that cognitive processes are not only abstract symbolic manipulations but grounded in perceptual, motoric, or emotional experience (for an overview, see De Vega, Graesser, & Glenberg, 2008). Imagine, for instance, you are helping a friend to move into a new apartment. You have to carry many things (sofas, tables, books, porcelain, washing machine, hopefully no piano, etc.) from his old apartment to the furniture truck and then later from the furniture truck into the new apartment. It is very likely that you

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http://dx.doi.org/10.1016/j.actpsy.2015.02.008
0001-6918/

try to avoid carrying bulky objects and prefer to move objects which are easy to carry. The question arises whether the physical properties of the objects that we reason about have an effect on how we think about them and how we manipulate them in our mental representation. All experiments on spatial belief revision so far used objects such as mangos, oranges, and apples that can be considered "neutral" regarding their specific physical properties (e.g., Knauff, Bucher, Krumnack and Nejasmic, 2013). These objects are very similar regarding physical properties, weight, size, and so on and it has not been investigated so far whether properties of objects affect the process of reasoning. However, recent theories on "grounded" and "embodied" cognition suggest that bodily experiences with and physical properties of objects indeed matter when we reason about them, even if the properties are not relevant for the cognitive task at hand (Barsalou, 2007; Glenberg, Witt, & Metcalfe, 2013; Zwaan & Pecher, 2012). That is, although you just imagine you are moving your friend´s furniture you might prefer to reason about carrying a vase over towing a piano, although that all happens in your mind without any real physical effort. The aim of this paper is to study such effects of *grounded cognition* in the area of spatial belief revision, when people have to mentally — but not physically — relocate objects in their imagination to account for newly available information during reasoning.

The structure of this article is as follows. First, we report some empirical findings on the link between grounded cognition, spatial reasoning, and belief revision. Second, we describe how our research is related to previous work on spatial mental models and then develop our hypotheses on how physical object properties should impact mental spatial belief revision. Third, we test these hypotheses with three experiments. Finally, we discuss our findings and draw some general conclusions on the connection of mental models, grounded cognition, and spatial belief revision.

2. The link between grounded cognition, spatial reasoning, and belief revision

The theory presented in this paper postulates that when individuals are confronted with a spatial belief revision problem, they first construct a mental model of the described state of affairs. If they are confronted with new information which is inconsistent with this initial model they vary the model in order to obtain consistency (Johnson-Laird, Girotto, & Legrenzi, 2004; Ragni & Knauff, 2013; more details are described below). The experiments concern the question if and to what extent the properties of objects such as size, movability, weight, and the potential bodily experience with these properties in the physical world affect the model variation process. For example, when people carry small or bulky objects this engages their muscles in the arms and legs differently. The hypothesis that we test in this paper is that during mental reasoning people simulate this bodily strain in their imagination and therefore also prefer to move handy sized objects over bulky ones in their mental representation. The theoretical background and the empirical evidence for this assumption are as follows.

2.1. Grounded cognition and object properties

Classical theories of human cognition rely on the idea that human thinking is based on an abstract language of thought (Anderson, 1993; Fodor, 1975; Pylyshyn, 1984). Arbitrary symbols stand for what they represent and humans are equipped with mental procedures to combine and manipulate theses abstract symbols. The results of such syntactic mental operations are again abstract symbol structures. Meaning arises from the combination of symbols that are arbitrarily related to what they signify (Glenberg & Robertson, 1999). The body and the information from the brain's modal systems for perception and action play, if any, just a marginal role because the symbols represent meaning in an abstract way that does not capture modality-specific information about the physical properties of objects, actions, or events. This classical approach is supported by numerous experimental findings and was very important for the development of cognitive psychology (e.g., Adler & Rips, 2008; Anderson, 1983, 1993; Pylyshyn, 2006; Rips, 1994). Today this classical approach is criticized by many psychologists. Some argue that the approach must be complemented by theories paying more attention to the representation of bodily experiences (Barsalou, 2007). Others are even more radical and completely deny the existence of abstract symbols in the human mind (e.g., Glenberg et al., 2013). The common idea of all these approaches is that people's understanding of language and memory representations are grounded in their physical interactions with the world (Beveridge & Pickering, 2013).

In fact, many authors reported that the processing of information in the mind is largely affected by the physical characteristics of the human body. For example, Glenberg and Kaschak (2002) asked participants to make judgments on sentences that describe actions toward the body (e.g., "Mark dealt the cards to you") or away from the body (e.g., "You dealt the cards to Mark"). The authors found that participants responded faster when the response requires an arm movement in the same direction as the action described by the sentence, which is called the Action-Sentence Compatibility Effect. Stanfield and Zwaan (2001) found that participants can respond faster to a picture of a *vertical* nail following the sentence "Mary pounded the nail into the floor" than after the sentence "Mary pounded the nail into the wall". The reverse response times were found for a picture of a *horizontal* nail. Proffitt (2006) studied visual perception and showed that people overestimate distances when wearing a heavy backpack or when of low physical fitness. Based on these findings, Proffitt argued that the perceived distance is affected by the bodily effort needed to traverse the distance.

The reported findings are only a few under many other results suggesting that simulated bodily states can affect mental states (Barsalou, 2008; Barsalou, Simmons, Barbey, & Wilson, 2003; Lakoff & Johnson, 1980; Smith, 2005). The theory of grounded cognition is also supported by functional brain imaging studies showing that the neural systems for meaning and action are reciprocally connected with each other (Isenberg et al., 1999; Martin & Chao, 2001; Gernsbacher & Kaschak, 2003; Kan, Barsalou, Solomon, Minor, & Thompson-Schill, 2003; Zwaan, Taylor, & de Boer, 2010; for an overview see: Pulvermüller, 1999).

Of particular importance for the present topic are cognitive studies on the effect of cognizing object properties such as size, weight, or movability. The question here is whether or not things that are hard to physically move are also hard to imagine moving. Flusberg and Boroditsky (2011) investigated this question by asking participants to manipulate wooden objects similar to the figures in the classic mental rotation experiment by Shepard and Metzler (1971). In the experiments, the wooden objects were mounted on rotation platforms with either empty devices or devices filled with sand. Thus, one pair of objects was easy to physically rotate while another pair was difficult to rotate, because of the sand. Flusberg and Boroditsky (2011) reported that participants were slower to mentally rotate objects that were harder to physically rotate. Object properties obviously had an effect on motor imagery. Similar results are reported in a study by Amorim, Isableu, and Jarraya (2006), who could demonstrate a cognitive advantage of imagined spatial transformations of the human body over that of more unfamiliar objects. These results, along with related findings have been used to argue that there is a close relationship between perceptual and motoric experiences and mental imagery (Barsalou, 2008; Kosslyn, Ganis, & Thompson, 2006).

A further characteristic of grounded cognition is to emphasize the importance of perspective taking in spatial thinking and language. Perspective taking means that it matters whether people mentally represent a scene from their own or a different spatial perspective (Kosslyn, Ganis, & Thompson, 2001; Pulvermüller, 2005; Rizzolatti & Arbib, 1998). Further, and probably more important, for embodiment theories it also matters whether persons simulate an action as if they were performing the action, or as if another person performs the action

(Beveridge & Pickering, 2013). In the present paper, we account for perspective-taking by explicitly asking the participants to image to be part of the scene. Thus, our problems always consisted of two objects and the participant as a third "object". An example for our problems is: "The piano is to the left of you.", "You are to the left of the sofa." How are the named objects arranged? In the next step a contradictory fact was presented, as we describe below.

Several studies suggest that our phrasing of the problems lead a participant to mentally simulate executing an action himself or herself. For instance, some authors could show that humans adopt a perspective automatically for sentences in which a self-referential pronoun is used and specifies the person as the agent of the action (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005; Willems, Hagoort, & Casasanto, 2010). Rizzolatti and Arbib (1998) showed that only if people imagine active physical interactions with objects this results in activity in areas of the motor cortex (see also: Kosslyn et al., 2001; Pulvermüller, 2005). Other studies showed that a certain perspective and additional bodily information may facilitate human reasoning (Beveridge & Pickering, 2013; Flusberg & Boroditsky, 2011; Galati & Avraamides, 2013; MacWhinney, 2005).

2.2. Spatial reasoning with mental models

The grounded cognition theory has been applied to many areas of psychology including concept representation (Barsalou, 1999), memory (e.g., Glenberg, 1997), language understanding (Glenberg & Kaschak, 2002; Zwaan, 2004), and social psychology (Barsalou et al., 2003). However, it has not yet been connected to the area of human reasoning, in which psychologists explore how people infer new information from what is already given (Johnson-Laird, 2006, 2010; Johnson-Laird & Byrne, 1991; Knauff, 2013). The lack of such a connection is surprising as the dominant theory of reasoning, the theory of mental models, and the grounded cognition framework share many basic assumptions. The central assumption that both theories have in common is that human cognition relies on *mental simulations*. Grounded cognition postulates that people understand sentences by mentally simulating what is described in the sentences. And it is assumed that humans reason by mentally simulating the content of an inference problem and then inspecting this model to find new information not explicitly given. In fact, both theories (grounded cognition and mental models) are also historically intimately linked (Bower, 1972; Glenberg & Robertson, 1999; Johnson-Laird, 1989; Kintsch & Van Dijk, 1978).

Today the vast majority of reasoning researchers considers the theory of mental models as the empirically best supported theory of human *spatial reasoning* (Johnson-Laird & Byrne, 1991; Knauff, Rauh, & Schlieder, 1995; Vandierendonck & De Vooght, 1997; Knauff, Rauh, Schlieder, & Strube, 1998; Schaecken, Girotto, & Johnson-Laird, 1998; Ragni, Knauff, & Nebel, 2005; Rauh et al., 2005; Krumnack, Bucher, Nejasmic, & Knauff, 2010; Krumnack, Bucher, Nejasmic, Nebel, & Knauff, 2011; for an exception see: van der Henst, 2002). According to Johnson-Laird (Johnson-Laird, 1983, 2006, 2010; Johnson-Laird & Byrne, 1991) a mental model is a mental simulation of the information presented in the reasoning problem. That is, the diverse pieces of information from the premises are not kept as separate entities in the reasoners mind. Rather, they are merged into a model that simulates the information given in the problem description, when it is constructed consistently. According to the mental model theory, people translate a perceived or imagined situation into such a mental model and use this representation to solve associated inference problems (Johnson-Laird, 1983, 2001, 2006, 2010; Johnson-Laird & Byrne, 1991). A central assumption of the mental model theory is that a reasoning process consists of three separate phases, which Johnson-Laird calls the comprehension, description and validation phases (Johnson-Laird & Byrne, 1991). In our previous publications, we suggested to use the terms *model construction*, *model inspection*, and *model variation phase*, because these terms characterize better what actually happens in these phases (Knauff, 2013; Knauff et al., 1998; Nejasmic, Krumnack, Bucher, & Knauff, 2011; Nejasmic, Bucher, & Knauff, 2015). In the model construction phase, people use the semantics of spatial expressions to construct an internal model of the state of affairs that the premises describe. In the model inspection phase, a parsimonious description of the mental model is constructed, including a preliminary conclusion. In other words, the mental model is inspected to find out relations not explicitly given. In the model variation phase, people vary the model in order to find alternative models.

The present paper is primarily concerned with the model variation phase, in which people must vary an already constructed model to account for new inconsistent information. In our previous work, we have postulated three main principles for such spatial revision processes (Knauff, Bucher, Krumnack, & Nejasmic, 2013):

1. Spatial belief revision is based on the construction and inspection of mental models. If given premises are true, a unified mental model represents what is believed to be true. By using the meaning of assertions and general knowledge a single model of possibilities that is compatible with these assertions is constructed. Explicitly given spatial information are not represented one-to-one mentally, rather they are inherent in the mental model. In this way relations between objects can be identified by mental inspection processes (Goodwin & Johnson-Laird, 2005; Johnson-Laird & Byrne, 1991; Polk & Newell, 1995).
2. Spatial belief revision relies on the revision of mental models. Individuals revise a model if newly available information is inconsistent with the current model and the new information must be taken for granted. In this process, people first "decide" which of the information to retain and which one to discard. Afterwards a local transformation is accomplished in which tokens are moved within the model to new positions (Bucher, Krumnack, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012; Krumnack, Bucher, Nejasmic, & Knauff, 2011).
3. The model revision process is sensitive to the functional asymmetry between the "reference object" (RO) and the "located object" (LO). Previous authors suggested an asymmetric role of the two arguments in a verbatim spatial description: The RO is interpreted as a landmark whose location is fixed and known, whereas the LO is located in relation to the RO and seems to be spatially more flexible. The common idea of all these accounts is that a spatial relation refers to the position of a particular object in focus relative to another object or area (Landau & Jackendoff, 1993; Miller & Johnson-Laird, 1976; Talmy, 1983; Tenbrink, Andonova, & Coventry, 2011). For instance, assuming that an initial model A–B–C is constructed and an inconsistent, but incontrovertible statement "A is to the right of C" is given. In this case C is the RO and A the LO. To regain consistency between the model and the inconsistent statement, the LO (A) of the inconsistent statement is relocated within the initially constructed mental model (resulting in a model B–C–A), also known as the LO-principle (Bucher et al., 2011; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Bucher & Nejasmic, 2012; Knauff et al., 2013; Bucher, Nejasmic, Bertleff, & Knauff, 2013; Mikheeva, Bucher, Nejasmic, & Knauff, 2013; Nejasmic, Bucher, Thorn, & Knauff, 2014).

In the present research, we use the stability of the LO-principle and test whether the effect is modulated by a person's bodily experiences with the interaction and manipulation of objects in the real world. Can the embodied aspects of the objects in a model weaken the LO-principle? Does the physical weight, size, or movability of the objects in the mental model influence how the model is revised? Based on previous findings within the grounded cognition framework, we predict that object properties such as weight, size, and movability indeed should affect the revision process. In general, we assume that the effect of the LO-principle can be weakened when the LO represents an object with a "disadvantageous" physical property (heavy, large, or unmovable) compared to an LO with a comparably "advantageous" property (light, small, or movable). When reasoners make use of mental simulations during the revision process, we expect them to mentally simulate the action of relocating real objects in the physical world. Thus, our main assumption is that objects with "advantageous" properties should be relocated *more often* or *faster* compared to the "disadvantageous" objects in the mental model. We also expect that these effects should be differently pronounced for different object properties, such as size, weight, or movability.

We now present three experiments that tested these hypotheses. In the experiments, participants received information about the spatial relations between objects which were either light or heavy (Experiment 1), small or large (Experiment 2), or movable or immovable (Experiment 3). The participants' task was to revise an initially constructed mental model after receiving a new contradicting piece of information. Prior to the main experiments, we conducted a pilot study during which participants rated objects according to a number of physical properties. The most appropriate items were subsequently chosen as objects for the main experiments.

3. Pilot study

Our first task was to define the set of objects for our experiments. One option would be to use the actual physical measures. However, we decided that for a psychological study it is more important how the objects are mentally represented and how people judge the weight, size, and movability of diverse objects. Certainly, the physical and the "psychological" proportions should be highly correlated and there should also be a correlation between weight, size, and movability (in the present study the ratings correlated as follows: size-weight: $r = .86$, $p = .000$, $N = 60$; size-movability: $r = .51$, $p = .000$, $N = 64$). To avoid confounds between the properties within experimental objects, we used only these objects from the large sets of objects rated in the pilot study whose ratings correlated least. Objects chosen for the pilot study were split into two sets of objects, rated by two different samples of participants in order to avoid lengthy rating experiments for the participants. The first list consisted of 60 objects. The objects were rated by 44 participants according to weight and size on five-point scales with the poles "very light" to "very heavy" and "very small" to "very large". The objects were presented in randomized orders to the participants. We selected the objects that obtained the lowest and highest mean values on the weight-scale and medium values on the size-scale (in order to control for the object size), for Experiment 1. The second list consisted of another set of 64 objects (different objects than the first list), and was presented to a new sample of 46 participants. Participants rated the objects on five-point scales with the poles "very small" to "very large" and "very movable" to "very immovable", respectively. With this procedure it was possible to select objects that differed in their size but were rated as similar regarding their movability (and vice versa). Objects that obtained the lowest and highest mean values on the size-scale and mean values on the movability-scale were used in Experiment 2. Objects that were rated as lowest and highest regarding movability but comparable in size were used in Experiment 3. It is important to note that some objects of our pilot study are inherently movable or immovable and were rated by participants accordingly. For instance, our participants rated a "printer" as relatively small but immovable (due to the wiring), whereas they rated a "soccer ball" as small and highly movable. All objects used in the experiments and corresponding means are presented in Table 1.

4. Experiment 1: light vs. heavy objects

The first experiment investigated how the weight of the objects in a mental model affects spatial belief revision. Can weight override or modulate the LO-principle? Are light objects preferably relocated compared to heavy objects? Or do participants still prefer to relocate the object which is the LO of the inconsistent statement no matter whether it is light or heavy?

4.1. Method

4.1.1. Participants

Twenty-nine students from the University of Giessen (18 male; age: $M = 23.34$; $SD = 3.22$) were tested individually. They gave written informed consent and received course credit or were paid at a rate of 8€/h for their participation.

4.1.2. Materials, design, and procedure

Each participant solved 48 problems. Six practice trials (not analyzed) preceded the experimental trials. Participants received instructions on the computer screen. The structure of the problems was as follows: first, participants received sequentially two statements, also called premises (1, 2), which described the spatial relation between three objects, for example:

(1) "A is to the left of B"
(2) "B is to the left of C".

From these two premises, participants were asked to envisage the order of objects, here the three objects are in the arrangement A–B–C. Participants indicated the order they envisaged by choosing one of two arrangements (correct arrangement/correct arrangement mirrored) that were presented on the screen by pressing the corresponding response key (construction phase).

In the next step (inconsistency detection phase), participants were confronted with an additional statement. It was consistent with the initial premises and the arrangement in half of the problems; in the other half it was inconsistent. Participants had to decide whether or not the presented fact was consistent with the model and the premises or not. Here an example for an inconsistent statement: "A is to the right of C". This is the critical point in time where participants had to realize that something must be wrong with their initial mental model of the three

Table 1
Objects used in the experiment according to their property with respective means and correlations.

Light	Heavy	Small	Large	Movable	Immovable
Fishing rod	Jukebox	Screen	Power mast	Wheelchair	Pillar
Beach towel	Sofa	Vase	Bridge	Bicycle	Counter
Sleeping bag	Icebox	Printer	Railway station	Carriage	Gravestone
Sheet	Stone bench	Post	High rise	Scooter	Oven
Curtain	Piano	Lamp	Spire	Barrow	Hydrant
M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)
Size/weight	Size/weight	Size/movability	Size/movability	Size/movability	Size/movability
3.0 (0.8)/1.9 (0.8)	4.1 (0.7)/4.6 (0.6)	2.4 (0.6)/2.8 (1.0)	4.6 (0.5)/1.2 (0.5)	3.0 (0.6)/4.1 (0.8)	3.0 (0.7)/1.5 (0.7)
$r = .37$, $p = .542$	$r = .29$, $p = .639$	$r = -.88$, $p = .051$	$r = -.73$, $p = .165$	$r = -.80$, $p = .106$	$r = .45$, $p = .449$
$r^2 = .14$	$r^2 = .08$	$r^2 = .77$	$r^2 = .53$	$r^2 = .64$	$r^2 = .20$

objects, not all three statements could be true at the same time. The third statement contradicts the inference from the first two statements. Crucially, participants were told that the third statement is irrefutably true such that they could not ignore the third statement. In cases where participants decided that the fact was inconsistent, they were asked to revise the arrangement, which means that they subsequently chose one out of two revised arrangements presented on the screen by pressing the corresponding button (revision phase). If the first premise is discarded this results in the arrangement B–C–A; if the second premise is discarded this results in the arrangement C–A–B. It is essential to see that the first revision strategy corresponds to the LO-relocation, whereas the second revision strategy means that the RO is relocated.

To study the effect of object weight the terms, A, B, C were instantiated with the light and heavy objects from Table 1. Further, by integrating a "you" into the problems, we encouraged participants to feel as the agent of the scene and to use an own-body-centered frame of reference (see above; Hauk et al., 2004; Pulvermüller et al., 2005; Willems et al., 2010). We expected that this would foster the perspective taking and that the participants are therefore even more sensitive to the object properties (see Section 2.1). Here is an example problem:

Premise 1	"The piano is to the left of you."
Premise 2	"You are to the left of the curtain."
Initial model	Piano–you–curtain
Inconsistent fact	"The piano is to the right of the curtain."

Revised orders:

You–curtain–piano ("relocation of the heavy object")

Curtain–piano–you ("relocation of the light object").

In half of the problems the heavy object was the LO and the light one the RO, in the other half it was reversed. All statements used the spatial relations "left of" and "right of" and were presented sequentially. Positions of the objects (i.e., light and heavy objects in the first, second, and third position) as well as the spatial relations used in the premises ("left of" and "right of"), were counterbalanced across the experiment.

Stimuli were presented and data recorded, using Superlab 4.0 (Cedrus Corporation, San Pedro, CA, 1999–2006). The experiment was run on a custom personal computer (Windows XP) with a standard 19″ monitor. Participants provided answers using an RB-530 response box (Cedrus Corporation, San Pedro, CA, 1999–2006). The program recorded (1) the number of correct responses in the "construction" and "inconsistency detection phase", (2) which object (LO or RO) was relocated in the "revision phase", and (3) how much time the participant needed to make the decision.

4.2. Results and discussion

Participants selected the correct arrangement in 94% ($SD = 8.11$) of the problems (construction phase). Inconsistencies between the initial information and the contradictory fact were correctly detected in 83% ($SD = 22.74$) of the problems (inconsistency detection phase). Erroneous trials were excluded from further analyses.

ANOVAs with the factors object weight (light vs. heavy) × functional asymmetry (LO vs. RO) were conducted for the revision choices and the respective revision times. Level of significance was 5%.

4.3. Revision choices

ANOVA for revision choices revealed a significant main effect of the LO–RO-asymmetry, $F(1, 26) = 37.17$; $p < .001$; $\eta^2 = .58$. As depicted in Fig. 1 participants relocated more often the fact's LO ($M = 72\%$, $SD = 21.65$) of an inconsistent fact within a mental model to regain consistency compared to the RO ($M = 27\%$, $SD = 23.96$), $t(27) = 6.41$; $p < .001$, $d_z = 1.21$. All other analyses, both for the main effect of object weight as well as the interaction were non-significant (all $ps > .50$).

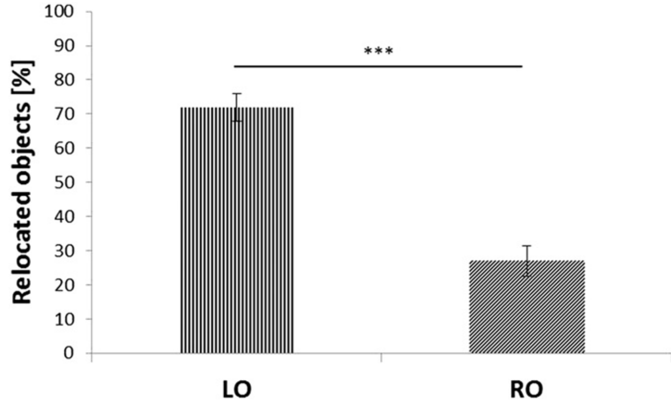

Fig. 1. Relative frequency (in %) of model choices based on the relocation of a fact's LO vs. RO in Experiment 1 (light vs. heavy objects). Error bars show standard errors.

4.4. Revision times

In an ANOVA, none of the differences in the revision times were significant (all $ps > .10$).

The results of our first experiment show that participants had a clear preference to relocate a fact's LO compared to the RO in order to regain consistency. This finding has some important theoretical consequences and corroborates our previous results of a strong asymmetry between RO-relocation and LO-relocation (Bucher & Nejasmic, 2012; Bucher, Nejasmic, Bertleff, & Knauff, 2013; Bucher et al., 2011; Knauff et al., 2013; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Mikheeva, Bucher, Nejasmic, & Knauff, 2013; Nejasmic et al., 2014). Particularly, the findings are hard to explain based on abstract, purely propositional representations of spatial relations. If relations were mentally represented as propositions of the form $r(A, B)$, where A and B are the objects to be located, we should not find an asymmetry between LO and RO. If, however, the participants mentally simulated the relations in a mental model and afterwards revised this model, this might account for the asymmetrical roles the objects play during the processing of spatial relational expressions. In fact, this assumption is supported by several experimental findings. Logan (1994, 1995) showed that if individuals are asked to verify spatial relations in a diagram they shift visual attention to the region where the LO is expected (see also Oberauer & Wilhelm, 2000). Hörnig et al. (2005) explored the integration of new premise information into an existing model and found that people integrate the LO of a relation faster if the RO of the premise was already part of the existing model. In our previous experiments, we were able to show that such directionality effects also play a key role during mental model revision (Bucher & Nejasmic, 2012; Bucher et al., 2011; Bucher et al., 2013; Knauff et al., 2013; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Mikheeva et al., 2013; Nejasmic et al., 2014). Our interpretation was that the RO–LO-asymmetry does not only influence how a model is constructed, but also have an effect when people already have constructed a model and then alter this model to account for newly available information. The findings support the model theory and also corroborate our main assumption that people reason by means of *mental simulations*. These simulations rely on people's actual interaction with the world and so also capture the asymmetries between a scene's reference objects and located objects also know from visual perception (Logan, 1994; Miller & Johnson-Laird, 1976).

The second finding of the experiment, however, is that the preference for LO-relocation is so strong that it could not be overwritten by the weight of the object. Even if the LO was the heavier object, it was relocated preferably. One possible explanation might be that people often have difficulties estimating the weight of an object by just looking at it or imagining it (Charpentier, 1891; Flanagan & Beltzner, 2000; Shim, Carlton, & Kim, 2004; Zhu & Bingham, 2010). However, our pilot study indicates that people are able to discriminate objects, not only in size and movability, but also in weight. Nonetheless, our participants were not inclined to use the type of objects as an indicator for physical effort.

A second possible explanation is that participants did not simulate the weight information, because some of the objects were in any event too heavy to be moved by a single person. The "light" objects were beach towels, sleeping bags, etc. All these objects we carry quite often in our everyday life. However, did you ever plan to move a jukebox or a piano just by yourself? Such items were used as "heavy" objects in our experiment, as they were rated in the pilot study as the heaviest objects. However, our study might indicate that passively rating the weight of an object is different from imagining to move the object. We think that here comes into play that, by integrating a "you" into the problems, we made participants feel as the agent of the scene and to use an own-body-centered frame of reference (see above; Hauk et al., 2004; Pulvermüller et al., 2005; Willems et al., 2010). We expected that this makes participants more sensitive to the object properties. If they were aware of the heaviness of the objects, participants were also likely to realize that the objects were actually too heavy to be moved by one single person. In this case, participants might have ignored the weight and might have also ignored it when they mentally relocated the objects. We think that this is an interesting issue for future research and might even turn into support for the grounded cognition hypothesis. However, in the next experiment we manipulated another object property — size — which might have a stronger effect on the revision choices.

5. Experiment 2: small vs. large objects

5.1. Method

5.1.1. Participants

A new sample of 21 students from the University of Giessen (nine male; age: $M = 22.86$; $SD = 5.27$) were tested individually. They gave written informed consent and received course credits for their participation.

5.1.2. Materials, design, and procedure

The instructions on the computer screen and the procedure were the same as in Experiment 1, with the difference that the objects used were small and large objects instead of light and heavy objects. Accordingly, the manipulated factors serving as independent within subject factors are: object size (small vs. large objects) and functional asymmetry (LO vs. RO). The same dependent variables as in Experiment 1 were of interest.

5.2. Results and discussion

Mean percentage rate of correctly constructed models was 98% ($SD = 2.15$, construction phase) and in 94% ($SD = 8.54$) of the inconsistent problems participants correctly identified the inconsistency between the initial model and the contradictory fact (inconsistency detection phase). Erroneous trials were excluded from further analyses. ANOVAs with the factors object size (small vs. large) × functional asymmetry (LO vs. RO) were conducted for the revision choice and the revision times, respectively. Level of significance was 5%.

5.3. Revision choices

The ANOVA for revision choices revealed significant main effects of object size, $F(1,20) = 5.75$; $p = .026$; $\eta^2 = .22$ and functional asymmetry, $F(1,20) = 63$; $p < .001$; $\eta^2 = .76$ (see Fig. 2; the interaction was non-significant, $p > .24$). Additional t-tests revealed that small objects ($M = 54\%$, $SD = 14.57$) were more often relocated than large objects ($M = 46\%$, $SD = 12.25$), $t(20) = 2.39$; $p = .026$, $d_z = 0.52$ (see Fig. 1) whereby LOs were still significantly more often relocated ($M = 80\%$, $SD = 24.66$) than ROs ($M = 20\%$, $SD = 15.91$), $t(20) = 7.91$; $p < .001$, $d_z = 1.73$.

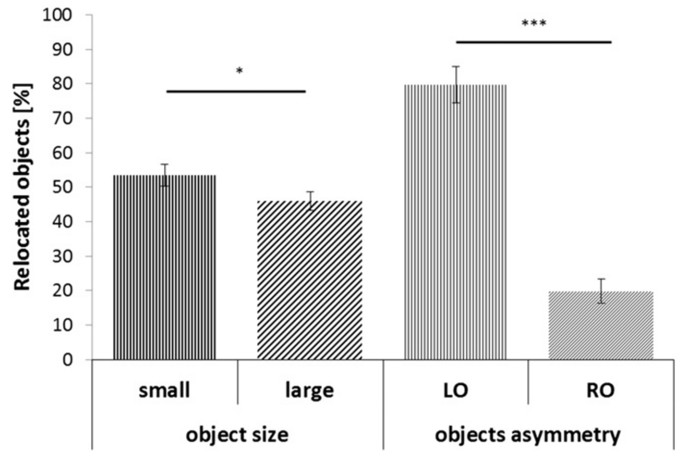

Fig. 2. Relative frequency (in %) of model choices based on the relocation of small and large objects, as well as of LO and RO in Experiment 2. Error bars show standard errors.

5.4. Revision times

Results of the ANOVA for revision times were non-significant (all $ps > .15$).

Experiment 2 shows that the physical size of objects had an effect on how people revised their existing belief about the arrangement of objects in space. Participants relocated small objects more often than large objects. The finding echoes what would be found in the physical world where small objects are more often transferred from one location to the other while large objects (like buildings) remain stationary. This finding agrees with the grounded cognition approach and is more difficult to explain based on purely symbolic cognitive theories. The finding also agrees with the mental model theory of reasoning, in which people reason spatially by constructing, inspecting, and varying spatial mental models that mirror the situation described in the premises (Knauff et al., 1995; Nejasmic et al., 2011; Ragni et al., 2005; Rauh et al., 2005). If such a model is then contradicted by a new fact, people try to revise the model by local transformations within this model. Results from the second experiment support the assumption that these mental operations are affected by the imagined size of objects. The underlying mechanism is most likely a mental simulation of the act of relocation, resulting in the preference to relocate small objects more often than large objects. In fact, the big objects such as railway stations or bridges used in this experiment are hardly ever relocated in real life while vases, monitors, and lamps are often relocated.

With the next experiment, we tried to replicate this effect with objects which were rated in the pilot study as movable or immovable. The question is again: does object property affect reasoning and belief revision? Is the physical challenge related to an immovable object somehow reflected when we manipulate it mentally?

6. Experiment 3: movable vs. immovable objects

6.1. Method

6.1.1. Participants

A new sample of 27 students from the University of Giessen (five male; age: $M = 22.81$; $SD = 6.29$) were tested individually. They gave written informed consent and received course credit for their participation. Data from one participant were excluded due to a technical problem.

6.1.2. Materials, procedure, and design

The instructions on the computer screen and the procedure were the same as in Experiments 1 and 2. Again, we manipulated two factors within this experiment: object movability (movable vs. immovable; see Table 1) and functional asymmetry (LO vs. RO) as the independent within subject factors. The same dependent variables as previously were of interest.

6.2. Results and discussion

Participants selected correct arrangements in 97% ($SD = 3.99$) of the cases (construction phase). They detected inconsistencies (inconsistency detection phase) between the initially constructed arrangements and the contradictory facts in 89% ($SD = 19.24$), correctly. Erroneous trials were excluded from further analyses.

ANOVAs with the factors object movability (movable vs. immovable objects) × functional asymmetry (LO vs. RO) were conducted for the revision choices and the respective revision times. Level of significance was 5%.

6.3. Revision choices

In this experiment, the ANOVA for revision choices again revealed a significant main effect of functional asymmetry, $F(1,24) = 120.60$; $p < .001$; $\eta^2 = .83$. Participants regained consistency more often by relocating the fact's LO ($M = 84\%$, $SD = 18.24$), compared to the relocation of a fact's RO ($M = 20\%$, $SD = 3.99$), $t(24) = 10.98$; $p < .001$, $d_z = 2.19$. In the revision choices, the differences between objects which are movable or immovable and the interaction were non-significant ($ps > .25$).

6.4. Revision times

The ANOVA for revision times revealed a marginal significant main effect of object movability, $F(1,10) = 3.80$; $p = .080$; $\eta^2 = .28$. A two-tailed t-test revealed that revision times were lower for revisions based on relocations of movable objects ($M = 2878.11$ ms, $SD = 1192.19$) compared to immovable objects ($M = 5302.12$ ms, $SD = 5785.98$), $t(25) = -2.45$; $p < .027$, $d_z = 0.46$ (see Fig. 3). In addition, ANOVA revealed a marginal main effect of functional asymmetry, $F(1,10) = 3.75$; $p = .082$; $\eta^2 = .27$ but subsequent analyses as well as the interaction were non-significant (all $ps > .10$).

The results of Experiment 3 demonstrate that participants did not prefer to relocate movable objects compared to immovable objects, but revision times differed significantly depending on the objects' movability. Participants needed less time to establish consistency between the initial premises and the fact, when the revision was based on a relocation of a movable object. This is what would also be expected when real objects in the physical world would be subject to manipulation. For instance, it is possible to relocate ovens, but it is more time consuming to move an oven than a wheelchair. Thus, participants needed less time to mentally "push" and relocate vehicles than relocating heavy ovens. This finding agrees with studies on the effects of mental motion on human reasoning and perception (Matlock, 2004; Richardson & Matlock, 2007) and with studies showing that a mental manipulation of objects is more time consuming if they are also harder to be moved physically (Flusberg & Boroditsky, 2011).

7. Overall mixed model analysis

We reported three experiments showing that different object properties have effects on different independent variables. In Experiment 1, we did not find reliable differences in revision preference and duration between light and heavy objects. The imagined weight of the manipulated objects did not affect the LO-preference. In Experiment 2, we found that the size of objects indeed affects the revision choice. Smaller objects were more often relocated than larger objects, what agrees with the grounded cognition hypothesis. But, we did not find reliable difference in the revision times. In Experiment 3, the pattern of results in revision choices and revision duration was reversed. Here, movability had an effect on revision duration but not on objects choices.

So far, we did not treat the experiments as a single study in order to exclude a possible crosstalk of the used object properties. However, the three experiments differed only regarding the type of objects (light vs. heavy, small vs. large, movable vs. immovable) and samples of participants. Therefore, we submitted the data to an overall analysis and computed additional ANOVAs. For the construction and inconsistency detection phase, ANOVAs were conducted with the three experiments as an independent variable and correct decisions as dependent variables, respectively. The ANOVA for the construction phase revealed a significant effect, $F(2, 73) = 3.65$; $p = .031$. Subsequent t-tests revealed that significantly more correct models were constructed in cases where small and large objects were used, compared to light/heavy $t(33.2) = 2.76$; $p = .009$, $d = -0.78$, and movable/immovable objects $t(39.7) = 2.27$; $p = .028$, $d = -0.60$. The error rates of the inconsistency detection phases do not differ between the experiments $F(2, 73) = 1.49$; $p = .231$.

Two additional ANOVAs were conducted with the factors objects' property (weight, size, movability) and the three experiments (1, 2, 3) as independent variables and the revision choice and the revision duration as dependent variables. In this way, it is possible to

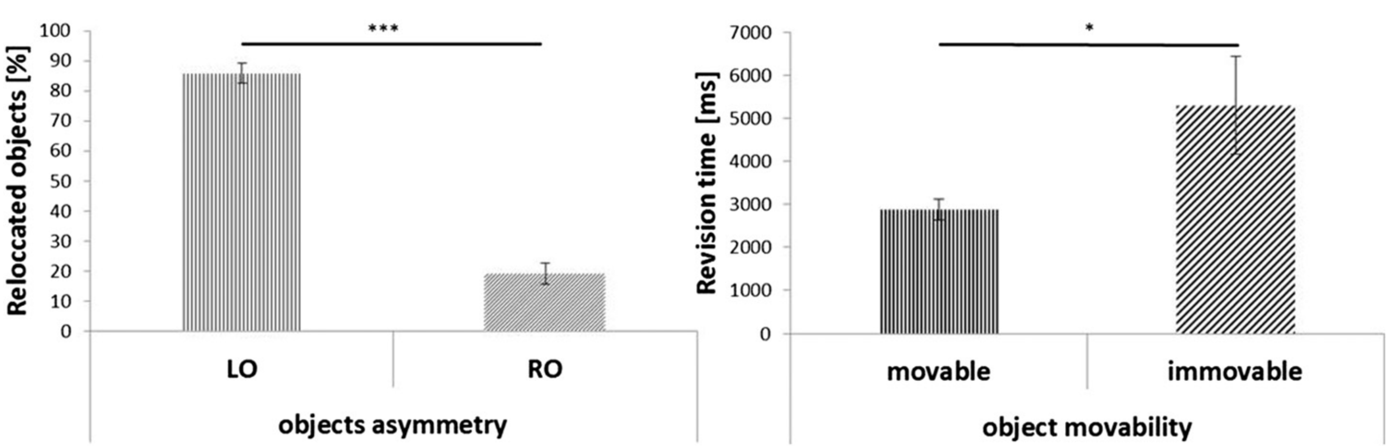

Fig. 3. Relative frequency (in %) of model choices based on the relocation of a fact's LO vs. RO and revision times (in ms) based on the relocation of movable or immovable objects in Experiment 3. Error bars show standard errors.

evaluate, whether different object properties would have different effects on different dependent variables, that is, revision choice and revision duration.

7.1. Revision choices

The ANOVA for revision choices revealed a significant main effect of objects' property, $F(1, 73) = 4.52$; $p = .037$; $\eta^2 = .06$. Participants regained consistency more often by relocating objects with "more advantageous" properties (light, small, or movable; $M = 52\%$, $SD = 14.63$), compared to objects with "more disadvantageous" properties (heavy, large, immovable; $M = 48\%$, $SD = 14.63$). The interaction was non-significant ($p = .49$).

7.2. Revision times

The ANOVA for revision times revealed a marginal significant interaction of objects' property × experiment, $F(2, 74) = 3.04$; $p = .054$; $\eta^2 = .08$. Subsequent one-tailed *t*-tests revealed significant lower revision durations for movable objects compared to light, $t(34) = -2.07$; $p = .023$, $d = 0.52$, and small objects $t(22) = 1.64$; $p = .058$, $d = 0.54$ (for an overview, see Table 2). In contrast, revision durations did not differ, for neither, immovable objects compared to heavy, nor to large objects (all $ps > .22$).

The analyses show for revision choices that all objects that are supposed to be classified as "in general more movable" or advantageous, either by a lower weight, by a smaller size, or by an increased movability, are relocated preferably, compared to the disadvantageous ones. In addition, taking a deeper look on these advantageous objects, the analyses show that the inherent motion of an object facilitates the relocation process compared to other advantageous objects resulting in lower revision times.

Table 2
Descriptive statistics of relative frequencies (RF in %) and respective revision times (RT in s) for the different object properties in Experiments 1–3 with corresponding standard errors (SE).

	Object properties					
	Light	Heavy	Small	Large	Movable	Immovable
RF (SE)	51 (3.4)	49 (2.4)	54 (3.2)	46 (2.7)	50 (2.5)	50 (2.5)
RT (SE)	7.1 (2.0)	4.3 (.75)	5.3 (2.4)	5.9 (2.0)	2.7 (.36)	5.1 (1.3)

8. General discussion

We reported three experiments on the connection of spatial belief revision and grounded cognition. We showed that spatial belief revision is sensitive (1) to the functional asymmetry between the reference object (RO) and the located object (LO) and also (2) to some (but not all) physical object properties. These results show that linguistic aspects and "embodied aspects" can interact if people revise an existing model in the light of new information. In the following we discuss both findings and draw some general conclusions on grounded spatial belief revision.

The finding that people have a strong tendency to relocate the LO rather than the RO agrees with previous findings (Bucher & Nejasmic, 2012; Bucher et al., 2011; Bucher et al., 2013; Knauff et al., 2013; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Mikheeva et al., 2013; Nejasmic et al., 2014). It also agrees with theories suggesting a strong link between thought processes and language (Clark, 1969, Polk & Newell, 1995). According to this theory each object in a spatial sentence plays a specific role and this might affect whether people are more inclined to relocate it or to keep it at its initial position. Basically, this theory states that functional relations, like the abstract subject–predicate relation that underlies sentences, do affect how humans reason, and, more precisely, also might influence how they revise an initial model (Clark, 1969, Polk & Newell, 1995). Our findings agree with this theory as participants seem to interpret the RO as more stationary whereas the LO is seen as more flexible. As a result, the LO-principle is the major revision principle applied by participants in all of our experiments. The result is robust and also appeared in previous experiments (Bucher & Nejasmic, 2012; Bucher et al., 2011; Bucher et al., 2013; Knauff et al., 2013; Krumnack, Bucher, Nejasmic, & Knauff, 2011; Mikheeva et al., 2013; Nejasmic et al., 2014). Moreover, our results support the assumption, that spatial belief revision includes a mental simulation of the asymmetry between a scenes reference object and located object.

According to the idea of grounded cognition, the mind is embodied, and thus cognitive processes must be grounded in perceptual, motoric, or emotional experience (for an overview, see De Vega et al., 2008). From this point of view, human thinking is based on perceptual simulations and modality-specific representations (Barsalou, 2008, 2010) and thus, we expected that object properties might influence how humans revise mentally spatial arrangements. To cope with the problem that properties are naturally correlated in objects, we disentangled them by experimental means and our results suggest that we were successful in doing so. This enables us to show for the first time that different object properties have different effects on spatial belief revision processes. Overall, the LO-principle is so strong that it is seldom overwritten by the imagined physical properties of the objects in the model. However, some object properties are more able to reduce the LO-preference while others are not.

Our findings also show that different psychological measures are sensitive to the effects of different object properties. On the one hand, size affected the frequency with which objects were mentally relocated, and thus participants preferably changed the position of small objects, whereby large objects were left in the same position. What happens when we transfer this result to the physical world? It basically means that a vase is relocated preferably to a house. That makes sense, given that we indeed relocate vases more often and more easily than houses. On the other hand, movability modulated the time individuals needed for the revision process. If movable objects were relocated, participants needed less time compared to immovable objects. This also agrees with real actions in the physical world and previous experimental findings (e.g., Flusberg & Boroditsky, 2011). Every-day experiences show that it is more time consuming to move an oven than a wheelchair. In this sense participants needed more time relocating stationary ovens than mentally "pushing" the wheelchair.

In almost the same manner we assumed that, for instance, a beach towel as a light object would be preferably or faster relocated than a jukebox or a piano (used as heavy objects in the experiment). But we did not find such an influence of objects' weight on our revision problems. While size and movability showed effects, it seems puzzling that weight did not. In the following, we discuss some possible reasons. One possible explanation is that participants in our experiments successfully simulated the weight information but did not take them into account for the revision process because the objects were too heavy to be relocated by one person where the first-person perspective was explicitly triggered by the experimental procedure. A second possible reason is related to recent studies, suggesting that the effects of "embodiment" on human reasoning and perception are probably based on experimental demand characteristics, i.e., that participants are aware of the experimenters' intention. For instance, some studies report that the fact to wear a heavy backpack might directly influence how humans perceive slopes and distances. In the studies the task was to estimate distances and slopes and the results show that participants overestimate them when wearing a heavy backpack. Such findings indicate that participants are subconsciously influenced by the weight of the backpack (Bhalla & Proffitt, 1999; Proffitt, Stefanucci, Banton, & Epstein, 2003; Proffitt, 2006). Nonetheless, there are also counter examples indicating that in such experimental settings participants were aware of the experimenters' intentions and shaped their answers accordingly (Durgin et al., 2009). Yet, in the present experiments it is unlikely that participants could guess the experimenters' intention, because the experimental variation was rather subtle and less obvious than in other studies (and our instruction was more neutral). In addition, we observed LO modulating effects of size and movability. Thus, a further possible explanation is motivated by studies suggesting that weight as an object property, is not simulated during reasoning. The argumentation is that humans have a hard time estimating the weight of an object by just looking or imagining it (Flanagan & Beltzner, 2000; Zhu & Bingham, 2010); despite their doubtless capability of deliberately discriminating object properties, as e.g., shown in the pilot-study where our participants were explicitly asked to estimate the size, movability, and the weight of a given object. However, the processing of the respective object characteristics during reasoning tasks, as required in the main experiment might involve more subtle cognitive processes which explains why weight did not influence spatial belief revision. The assumption is related to the LASS (linguistic and situated simulation) theory of conceptual processing (Barsalou, Santos, Simmons, & Wilson, 2008). During recognition of a presented word, the linguistic system activates correlated simulations in the brain's modal system. Based on this simulation, not only the general meaning of the processed word is represented but rather situated experiences are simulated, preparing agents for possible actions in particular situations. This is in line with the assumption that language comprehension involves perceptual simulations of a described scene, including a mental activation of possible actions a person can realize with the mentioned objects (Glenberg & Robertson, 1999; Kaschak & Glenberg, 2000). An important aspect in this context is that it seems to matter in what modality humans experience object properties. Simulations are supposed to be executed in the same brain areas that are also used for actually perceiving certain properties. Evidence is e.g., provided by studies using verification tasks, where humans are found to be faster and more accurate when a property is presented with a congruent object, i.e., an object sharing the same property as compared to an incongruent object (featuring a property that does not match the target objects property) (Pecher, Zeelenberg, & Barsalou, 2003, 2004; Spence, Nicholls, & Driver, 2001). In our experiments, simulations might have been strongest for properties according to which objects are easy to be judged from visual input: the size of an object is very directly visually perceivable, while the movability of an object is more subject to inference from other object features (e.g., has wheels). The weight of an object definitely needs to be inferred from its further characteristics. Observers appear to use an "indirect route" when estimating the weight of objects. They tend to infer the object's weight from the (directly estimated) velocity by which an object can be lifted, or they use the effort that it takes to lift it as a reference point for their weight estimation (Shim et al., 2004). For participants in our weight experiment, an indirect route — for instance via the estimation of the objects' size — was not accessible (since size was kept constant across light and heavy objects). Additionally, whereby everyone has experienced not less than once how large a church might be, or how a wheelchair is relocated, exceedingly few people might have experienced how difficult it is to relocate a piano. It seems plausible that as a consequence, weight was not found to alter the LO-principle, whereas this null effect regarding weight does not contradict grounded cognition assumptions.

In point of fact, our findings create new conceptions between grounded cognition and mental models. Today, the vast majority of researchers consider the mental model theory to be the empirically best supported theory of human spatial inference (Vandierendonck, Dierckx, & De Vooght, 2004; Goodwin & Johnson-Laird, 2005; Knauff, 2009, 2013; for an exception see: van der Henst, 2002). The present work shows that the idea of a mental simulation in mental models can also incorporate other physical features and that these features influence human reasoning as shown here in the case of spatial belief revision. In fact, the theory of grounded cognition and the theory of mental models make a good match. In particular, the mental model theory assumes that we reason using mental simulations, and infer from simulations what might be the case in a certain situation.

The present study followed the question whether object properties influence the way how humans revise their beliefs about spatial relations and results show that objects with more advantageous properties (light, small, and movable) are relocated preferably or faster (movable objects) over more disadvantageous objects (heavy, large, and immovable). More precisely, objects that suggest a motion like bicycles or wheelchairs are faster relocated than immovable objects like counters or stoves. These findings support the idea that people also consider their knowledge about physical object properties during spatial belief revision.

We summarize, that spatial belief revision can be influenced by object characteristics that are mentally represented. An important corollary from our study is that different object properties are not considered in the same manner for spatial belief revision. In fact, different object properties have different effects on grounded spatial belief revision. This is a novel finding and opens up new avenues of research on how humans mentally simulate actions with imagined physical objects during reasoning.

Acknowledgments

This work was supported by grants of the Deutsche Forschungsgemeinschaft (DFG) to Markus Knauff and Bernhard Nebel KN 465/6-1 and KN 465/6-2. We thank Isabell Tapia-Leon and Sören Studer for assistance with the experiments and the reviewers for many helpful suggestions to help improving the paper.

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