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TEST: A Tropic, Embodied, and Situated Theory of Cognition

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ABSTRACT

TEST is a novel taxonomy of knowledge representations based on three distinct hierarchically organized representational features: *Tropism, Embodiment, and Situatedness*. *Tropic* representational features reflect constraints of the physical world on the agent's ability to form, reactivate, and enrich *embodied* (i.e., resulting from the agent's bodily constraints) conceptual representations embedded in *situated* contexts. The proposed hierarchy entails that representations can, in principle, have tropic features without necessarily having situated and/or embodied features. On the other hand, representations that are situated and/or embodied are likely to be simultaneously tropic. Hence while we propose tropism as the most general term, the hierarchical relationship between embodiment and situatedness is more on a par, such that the dominance of one component over the other relies on the distinction between offline storage vs. online generation as well as on representation-specific properties.

135 words.

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Introduction

Classic theories of cognition (e.g., Fodor, 1983; Newell & Simon, 1972; Pylyshyn, 2009; Tulving, 1983) regard the human brain as an information processing machine operating on mental representations in the form of *amodal* encapsulated entities independent from the perceptions and actions of the agent interacting with the world. Such mental representations are essentially abstract symbols translated and divorced from sensorimotor experiences of the physical world and the body. As such, symbolic theories of knowledge representation postulate a separation between world, body, and mind.

Non-symbolic theories of cognition are significantly different from this classic view. They draw the focus away from the mind as a universal Turing Machine with the body as its mere input-output interface, towards the view that cognition relies on the experiences of the whole organism in its constant interactions with the environment. Crucially, according to this view it takes both the body and the world to form, integrate, and retrieve knowledge; hence, the corresponding mental representations[1], abstract or concrete, have to be *grounded* in the interactions between the cognizing organism and the environment it inhabits (e.g., Barsalou, 2008; Glenberg & Gallese, in press; Lakoff & Johnson, 1999). For a representation to be grounded, it needs to encode specific parameters of the physical world as well as the specific organization of the body. As Barsalou (2010: 717) suggests, a grounded mind "…utilizes the environment and the body as external informational structures that complement internal representations". Hence, grounding forms a fundamental assumption commonly shared by non-symbolic cognitive theories.

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[1] *Enactivist* and similar approaches to cognition refute the necessity of mental representations as primary units of thought by putting emphasis solely on the interaction between the body and the environment (e.g., Hutto, 2005; van Elk, Slors, Bekkering, 2010; Varella, Thompson, Rosch, 1991). We will continue using the term "mental representations" here in our attempt to hypothesize about their diagnostic properties. Our theoretical proposal can in principle replace "representation" with "knowledge" without changing its diagnostic hypotheses..

Another notion commonly shared by non-symbolic theories of cognition is that of *simulation* as a driving vehicle of knowledge retrieval. Different views of simulation have been proposed. One dominant view defines simulation as “the re-enactment of perceptual, motor, and introspective states acquired during experience with the world, body, and mind” (Barsalou, 2008: 618, see also Gallese, 2005; Hesslow, 2012, *inter alia*). In addition to the retrospective re-enactment of previously accumulated experiences, simulation theories emphasize that the simulation process makes it possible to predict (e.g., Barsalou, 2009; Clark, in press; Pickering & Garrod, 2009) and/or emulate (e.g., Colder, 2011; Moulton & Kosslyn, 2009) upcoming changes in the world including the cognizing organism’s behaviour and the behaviour of its conspecifics in the current and similar situations. In other words, simulation does not only underlie information retrieval, it also potentiates future actions by making predictions from past experiences. The balance between the retrieving and predictive aspects of simulation is beyond the scope of this article. Regardless of the exact properties of the simulation process, simulated knowledge is essentially grounded, multimodal, and integrated within the brain’s sensory and/or motor architecture. What is specifically relevant to the goals of our paper is, firstly, the fact that all simulation theories feature *the world, the body, and the situated context* among the informational building blocks of the simulated representations. Secondly, while simulations are largely based on prior experience with the world—i.e. on multimodal information that is stored offline—the process of simulation itself happens online, i.e. in the ‘here and now’ of cognitive processing.

In a similar vein, we do not propose that all concepts are necessarily simulated or that all representations require the same amount of simulation. A number of recent theoretical proposals emphasize the need for multiple representational systems including both embodied and “dis-embodied” (i.e., abstract) concepts (e.g., Barsalou, 2008; Dove, 2011; Gilead, et al., 2012; Louwerse & Connell, 2010; Markman & Brendl, 2005; Wilson, 2002). The question of *what* abstraction is with regard to simulation is very important; here however, we simply follow the working hypothesis that the required degree of simulation can be viewed as inversely related to the required degree of abstraction: A more automated and engrained representation requires less and/or more shallow simulation for adequate retrieval, thereby implying higher degrees of abstraction (e.g., Chatterjee, 2010; Johnson, 2007, Tucker, 2001).

So, what body/world parameters are known to be simulated during knowledge retrieval? In addition to well-documented simulation of the organism's embodied experiences (the body), two further components include "tropism", i.e. the objective organization of the physical world (see further below) and "situatedness", i.e. the given context in which the knowledge is retrieved. The latter is different from the world *per se* in two ways. First, contexts are not "objective", they form the subset of the environment perceived as relevant to the agent's goals and actions. Second, relevant contexts may be physical, social, introspective, etc.

The dynamic relationship between these three components (tropic, embodied, situated) is the focus of our paper. In the remaining paragraphs we discuss the proposed relational taxonomy with regard to three different functional aspects of simulated representations: (1) the individual diagnostic features of the world-specific, the body-specific, and context-specific components, (2) the hierarchical relationship between them, and (3) their specific instantiations in relation to the distinction between online (e.g. simulated) and offline (stored) representations (e.g. Wilson, 2002). We believe it is essential to make and explain these distinctions in order to resolve some of the present confusion in the literature, where labels such as "grounded", "embodied", or "situated" processing have often been ill-distinguished or used interchangeably, making concrete and falsifiable predictions impossible.

TEST: A theory of Tropic, Embodied, and Situated Cognition.

Cognitive Tropism

Our attempt to explain how the world, the body, and the context interact as components of multimodal representations starts with a perplexing observation: There is no good term for the specific effects of the world on mental representations. Previous work by Kessler & Rutherford (2010), Myachykov, Platenburg & Fischer (2009), and Pezzulo et al. (2011) advanced the idea that the special role of world-related simulation can be referred to as a form of *grounding,* meaning that it reflects features and constraints of the physical world in which the representations were acquired and in which they become continuously reactivated. However, as we have already noted, grounding also (and more conventionally) refers to modal or multimodal ways of representing abstract knowledge and not necessarily knowledge about the world. As we will show, effects of the physical world on mental representations can be quite specific; hence, we decided to borrow the concept of *tropism* from another scientific discipline, i.e., plant biology.

It is commonly known that the forms and shapes of plants are a result of environment-driven adaptation processes. Interestingly, plants' behaviour also reflects the organization of the surrounding environment. This phenomenon, known as *tropism,* refers to the plant's specific response (e.g., direction of growth) as a result of changes in environmental stimuli, such as, light, gravity, temperature, presence/absence of water (Garzon & Keijzer, 2011; Karban, 2008; Kiss, 2006; Poff, et al., 1994). Specific types of tropism include gravitropism (movement or growth in response to gravity), heliotropism (movement or growth in response to solar activity), phototropism (movement or growth in response to light or colour).

In analogous fashion, we propose a hierarchy with representational *tropism* as the most general, stable, and automated component within multimodal representations, while *embodiment* and *situatedness* are more specific notions. This proposal results in a hierarchical system of Tropic, Embodied, and Situated Theory of Cognition (TEST). Table 1 provides a very basic and minimal summary of specific representational components, their associated domains, and stability parameters.

=====insert Table 1 about here=====

Tropic representations are the most stable representations, because they reflect aspects of the environment that are stable. This notion of stability refers to invariant features of the environment, the body, and situational context that can be extracted and consolidated into long-term memory across time and repeated occurrences. In the most general terms, our proposal suggests that these three different forms of experiential cognition are associated with different degrees of stability which makes them more or less malleable to training and retraining. Although the proposed taxonomy puts tropism at the top of the hierarchy, the other two components are more equally weighted. For offline (stored) representations we argue that embodied representations are moderately stable because they are sensitive to individual differences in long-term sensory-motor experience (e.g. handedness, blindness, deafness), while situated representations are less stable because they reflect aspects of the current context in which an agent is interacting (e.g. task-specific variations).

For online processing (which typically involves simulation) we will also argue that, due to their primacy and stability, *tropic* concepts require little depth of simulation, are not easily retrained, and are largely due to environmental regularities. In contrast, offline *embodied* representations are largely due to bodily regularities. They would remain more open to retraining and would require more depth of online simulation for retrieval. Finally, *situated* representations rely more on momentary context of the environment and/or the agent; like embodied representations, they would also be more easily retrained and would require deeper online simulation. Note that for online processing the agent's body provides a particular aspect of the wider situational context that can be recruited for representation or not. Hence, the hierarchy between embodied and situated processing may depend on whether one focuses on stored representations or on online processing as will be further elaborated in the next section.

Similar to tropism in plant biology, *tropic* components of knowledge may reflect world features such as gravity, sun-related cardinal orientation, and vertical accumulation of objects and quantities. The fact that humans share "the same world" leads to the primacy of the tropic representational component, as well as its ubiquitous presence in many stored and simulated representations. To be clear, this does not imply that every multimodal representation must be tropic. It does, however, imply that, when present, the tropic component is the same regardless of other, variable, simulation constraints (such as individual bodily difference, language, or social context). One example of universal tropism is the tendency to represent increasing numerosities along the upward oriented vertical spatial axis—'more' means 'piling up' in a direction opposite to the effect of gravity.

We further suggest that statistical invariances of tropism across a variety of occurrences often become part of a representation's core (e.g. "down" always points in the direction of gravity), while the unique tropism of a particular cognitive instance can influence the instantiation of a representation *online* in a particular situation (e.g. "down" would become more visually defined during parabolic flight, when gravity is removed, e.g. Dalecki et al., 2012).

Situatedness and embodiment

Further to representational tropism, conceptual representations can be embodied if they encode the agent's bodily state during the acquisition, generation, and comprehension of conceptual knowledge. In this respect, embodied properties code both the bodily features shared with other conspecific organisms as well as features specific to an individual organism. The distinction between *offline* and *online* modalities (Wilson, 2002) becomes essential in this context: Motor programs common to all occurrences of a concept become part of the long-term core representation. We propose that embodied components become the core of offline representations whose parameters were shaped by the general constraints of the human body (e.g. opposable thumbs or frontal vision). For example, humans use a number of different simulation frames in order to conceptualize time, one of which is along an egocentric forward-oriented axis, congruent with moving forward through physical space. Hence, idiosyncratic corporeal arrangements (e.g. being born without arms) should shape the individual's particular representational features in relation to the affordances within the world.

Congruent with our notion of tropism, simulated representations can often be embedded within (and constrained by) a situational context; that is the agent's specific interpretation of the environment with regard to his or her goals. Hence, conceptual representations are situated because they reflect the specific contexts, within which they are formed and used. Common situated features can be extracted as invariants and also become core parts of offline representations (e.g., left-to-right reading direction or social conventions in general, e.g. polite speech). In some cases, these situated features are less fundamental than the tropic constraints or, as we will discuss below, the constraints imposed by the body. In other cases, situated parameters may dominate over embodied ones when the role of bodily states is a "weaker" contributor than the context during a particular online simulation. For example, one might be more inclined to adopt the child’s spatial perspective when interacting with a child independent of current bodily constraints. Hence, in the online modality, embodied simulation can be quite specific as it involves the most specific representational features. In other words, bodily experiences need to be an essential part of a simulation process to fulfil the definition of online embodiment beyond existing physical and contextual constraints.

There are a couple of important features related to the specific hierarchical relationship between tropic, embodied, and situated features in a given representation. First, the proposed relational hierarchy entails that representations can, in principle, be tropic without being situated and/or embodied. On the other hand, representations that are situated and/or embodied are likely to have tropic features as well (since situations and bodies are part of the environment). Hence, while we propose tropism as the most general term, the hierarchical relationship between embodiment and situatedness is more on a par, such that the dominance of one component over the other relies on the distinction between offline and online generation as well as on representation-specific properties. Second, our theory assumes that the distinction between the three proposed components is categorical: While a specific simulated representation can, in principle, contain any combination of the three components (for instance, a given representation may be regarded as both tropic and embodied), we initially do not propose a “graded” distinction whereby the three components are just “short-hands” for different levels of representational stability along a continuum. In our view, a categorical distinction is better suited to generating falsifiable hypotheses, by specifying both quantitative and qualitative diagnostics for each individual component.

Therefore, our proposal makes a step towards unifying theories of simulated cognition by deriving diagnostic features from the proposed relationships between tropism, embodiment and situatedness. Prominently, these include the following dimensions: (1) the requirements for, and the "depth" of the involved cognitive simulations, (2) the steepness of learning and re-training gradients of specific features in offline representations, and (3) the degree to which a particular conceptual representation depends on the online constraints provided by the mental representations of the world, the body, and/or the situational context. These diagnostic features lead to concrete hypotheses that we will outline below.

In the paragraphs that follow, we provide examples of tropic, situated, and embodied knowledge representations in three areas of cognitive research: Abstract language, understanding numerosities, and perspective taking in communication. We will use the domain of abstract language in order to demonstrate the presence of individual and distinct diagnostic representational features that reflect tropic, embodied, and situated components. We will then discuss recent evidence from numerical cognition in an attempt to demonstrate how the proposed (offline) hierarchy of (stable) tropism, (less stable) embodiment, and (dynamic) situatedness is reflected in the relative ease of their re-training. Finally, in order to highlight the importance of online versus offline properties of simulated representations, we will bring forward examples from research on perspective taking. We will conclude with suggestions for further research.

Abstract language: A case for the specific diagnostic features of TEST components

Human language and linguistic behaviour provide arguably the most diverse testing grounds for multimodal and simulation-based theories of cognition. In part, this is a result of the ability of lexical concepts to carry both concrete and abstract meaning. Recent behavioural (e.g., Glenberg & Kaschak, 2002; Zwaan & Taylor, 2006) and neuroscientific (e.g. Cacciari, et al., 2011; Hauk et al., 2004) studies convincingly demonstrate that in comprehension, words denoting concrete concepts activate distributed networks that include activation of sensorimotor components. More importantly, the same principle of representing language via modal systems holds true for abstract concepts (e.g., Barsalou & Wiemer-Hastings, 2005; Cacciari, et al., 2011; Gallese & Lakoff, 2005; Glenberg, et al., 2008) and even for some basic grammatical units of a language (e.g., Fazio, et al., 2009; Guerra-Filho & Aloimonos, 2012; Kemmerer, 2012; Pulverműller & Fadiga, 2010). Here we will use a couple of examples from language research showing how the proposed hierarchical taxonomy can be applied to abstract language.

Multidimensional mappings between abstract language about emotional valence (e.g., *good* vs. *bad*) and space are good examples of the relationship between tropic and embodied components in abstract language. Speakers of different languages consistently map vertical space onto the contrast between positive and negative abstract words denoting affect (e.g., *good* is *up*, *bad* is *down*). This *tropic* spatial mapping emerges from the collection of constantly performed motor functions resulting from our erect posture within the gravitational field we live in (Ortiz, 2011). Confirming this, Meier and Robinson (2004) demonstrated that a word presented at the top of the screen is recognized faster when it denotes a positive concept while negative-connotation words are categorized faster when presented in the bottom of the screen (see Crawford, 2009; Meier, et al., in press, for reviews of similar studies). A recent meta-analysis by Lakens (2012) suggests that this consistent mapping can be explained by *polarity differences* between the corresponding dimensions in the physical and emotional domains[2].

[2] It has to be noted that in Lakens's own data no consistent mapping from bad concepts to low space was found while good concepts were indeed processed faster in higher space compared to lower space.

At the same time, representing emotional words reveals an *embodied* mapping along horizontal space: Right-handers tend to associate *good* with right space and *bad* with left space (Casasanto, 2011, for a recent review). A recent study (Brookshire & Casasanto, 2011) showed that the processing of emotional words is also linked to the lateralized cortical representation of manual motor actions. Although the evidence from linguistic universals along the horizontal dimension is lacking, the proposed hierarchical dominance of tropism over embodiment would predict that embodied metaphorical mapping of emotional words onto horizontal space should be easier to un-train (or re-train) than the corresponding tropic vertical mapping component.

The multidimensional spatial mapping of emotional words also provides a window into the difference between shared (core) and individual-specific variants of the same representation. For example, one core element of the embodied horizontal-space mapping is associated with a culturally unspecific right-hand dominance in most speakers. This representational core reveals itself in the cross-linguistic prevalence of metaphors that consistently associate right with *good* (e.g., *right-hand man*) and *left* with *bad* (e.g., *"hodit' nalevo"* (*go left*) in Russian means to commit adultery). At the same time, an individual's handedness may modulate the directionality of the mapping: Left-handers demonstrate lateral representation of abstract emotional valence opposite to right-handers (Casasanto, 2009; Casasanto & Chrysikou, 2001). The latter is important as it suggests that, in contrast with numerosities (see following section), simulated representations of emotional words do not have a strong situated component that would similarly reflect situated contexts, such as reading direction. The recent discovery of the QWERTY effect (Jasmin & Casasanto, 2012) confirms that horizontal rightward mapping of affect reflects the prevalence of right- over left-hand dominant people rather than the organization of specific scripts.

Furthermore, although the vertically oriented tropic mapping of emotional words is shared by humans, it is subject to individual embodied tuning. For example, people with stronger embodied representations of affect also reveal a stronger association between affect and space (Moeller, Robinson, & Zabelina, 2008). Similarly, neurotic and depressed individuals reveal stronger lower/negative signatures of the vertical mapping of affect-related language (Meier & Robinson, 2006). Finally, individual differences in covert spatial attention predict the strength of the vertical mapping by modulating the speed with which participants react to vertically positioned probe words (Robinson et al., 2008).

An even more complex multidimensional spatial mapping is found in the linguistic concepts denoting time (Boroditsky, 2011, for a review). Words related to time perception appear to cluster within a three-dimensional space including (1) the embodied egocentric back-to-front perspective of the body's movement through space, (2) situated horizontal and vertical projections from the culturally specific organization of text, and (3) tropic projections of the geographical organization of the world, such as progression of the Sun from east to west.

The ubiquitous *embodied* component in our representations of time relates to the universal egocentric perspective of "moving" through time similarly to moving in space, with the future being *ahead* and the past being *behind* (Boroditsky, 2000). Because of the comparable bodily arrangement across speakers of different languages, this component constitutes the core of simulated representation of time in speakers of all human languages. At the same time, culturally specific contexts, such as reading habits, lead to the establishment of a distinct *situated* component in the simulated representation of time. Confirming this, Boroditsky (2001), Boroditsky, Fuhrman, & McCormick (2011), and Fuhrman & Boroditsky (2010) showed that the time perception of English, Mandarin, and Hebrew speakers differs in how speakers of these languages map the concept of time onto vertical and horizontal spatial arrangements, consistent with the direction of reading and writing. For example, Hebrew speakers reveal horizontal right-to-left mapping of time reversed from the one common in English speakers who represent time as progressing from left to right (cf. Fischer, Shaki, & Cruise, 2009, for a similar effect with number representation). Mandarin speakers, on the other hand, show a pattern not present in either English or Hebrew: Due to the vertical script arrangement they tend to think about time as progressing vertically downwards (see also Bergen & Lau, 2012 for similar findings on how writing direction maps onto time). Together with our discussion of similar effects in number processing (see below), these findings provide converging evidence for culturally specific situated features in representations that originate from different abstract knowledge domains. Consistent with predictions derived from our hierarchical view of tropism, situatedness, and embodiment, the shared embodied mapping of egocentric perception of time with future ahead and past behind should be harder to unlearn than the culturally assumed mapping along horizontal and/or vertical space resulting from culturally specific reading experiences.

It appears that the embodied core of the time concept is relatively immune to simultaneously representing any tropic features. Perhaps this is not too surprising given that time cannot be physically experienced as such. However, a recent report by Boroditsky and Gaby (2010) may point to some exceptions: Speakers of Pormpuraawan, an Australian Aboriginal language, were shown to represent time as progressing from east (past) to west (future), independent of viewpoint. This finding supports our notion of tropism by demonstrating how mental representations of time can encode the nature of the physical world independently of embodied or situated dimensions. Interestingly, a brief informal analysis of the etymology of the English word *West* shows that in the Early English period it also meant *evening,* the latter suggesting a tropic component in the concept of time. Supposedly, this tropic component became less relevant as the importance of organizing every-day life around sun cycles diminished for speakers of English. This hypothesis opens interesting possibilities for investigating similar properties in other languages. At the same time, the discussed examples demonstrate that tropic representations are not necessarily universal as there is cross-cultural variation as to how language is mapped onto experiences with the world.

It is also interesting to consider how different spatial axes can be related to specific bodily features. The typical human body has a clearly defined front (face), back (spine), top (head), and bottom (feet), while the left and right sides are visually quite symmetrical in terms of anatomic features. In terms of mappings of abstract concepts onto embodied spatial representations, these considerations lead to the general prediction that mappings in relation to axes with well-defined bodily asymmetries (i.e. vertical and front/back axes for concepts of valence and time) will result in the extraction of these asymmetries as permanently stored embodied representations. The corresponding mappings should be harder to re-train than mappings related to left-right space for which the human body is visually symmetrical and can, thus, only rely on "introspective" action-related asymmetries based on handedness. These considerations will play a prominent role in the next sections, particularly in the section on perspective taking and will be elaborated in relation to our online/offline distinction.

Numerical cognition: A case for the hierarchy and depth of processing

The field of numerical cognition is characterized by a large range of well-known performance signatures that indicate a complex interplay between perceptual, syntactic, semantic and strategic factors. For example, the size congruity effect (Henik

& Tzelgov, 1982) denotes a competition between the physical size and the magnitude meaning of visually presented numerical symbols, and the inversion effect (Brysbaert et al., 1998) describes a culture-specific directional conflict between linguistic and perceptual representations of multi-digit numbers (for a recent review see Nuerk et al., 2011).

Of special interest for the present debate is the SNARC (spatial-numerical association of response codes) effect, which indicates a pervasive association between numbers and space (for recent review see Wood et al., 2008). Indeed, as will be shown, the SNARC effect can serve as a test-bed for the hierarchical view of tropic, embodied, and situated representations of number magnitude, particularly from the point of view of the representational feature's stability. As stated earlier, we assume that tropic representations are the most stable because they reflect the most consistent learning experience, whereas embodied representations are less stable as they capture individual-specific sensorimotor experiences that reflect sensory-motor contingencies and the contextualized use of number magnitudes. Finally, situated number concepts are associated with space in the most flexible way because their availability is driven by online task demands. This proposed hierarchy makes it clear that our theory must consider both the diagnostic power and the relative depth of processing when discussing tropic, embodied, and situated representational properties.

Consider first the ubiquitous association between magnitudes and vertical space: Small numbers (1, 2) are usually associated with lower space and higher numbers (8, 9) with upper space. This association was experimentally documented for manual button presses (Ito & Hatta, 2004) as well as saccadic eye movements (Schwarz & Keus, 2004), and generalizes even to auditory frequencies (Rusconi et al., 2005; Fischer et al., in press). The vertical SNARC reflects the regular increase in height for larger accumulations of objects. It holds across cultures, as is indicated also by its universal metaphorical expression in language (e.g., “higher value”, “lower score”; see Lakoff & Johnson, 1980). As such, the vertical SNARC is present in offline as well as online knowledge representations. It is present even in participants who do not associate number magnitudes with horizontal space, e.g., due to conflicting reading habits for texts and numbers (Shaki & Fischer, 2012). Apparent counter-examples, such as league tables or negative temperature scales, reflect situation-specific exceptions that can be subsumed under this principle when considering the linguistic markedness of the respective concepts (less good, less warm).

A diagnostic feature of tropic number representations is their resistance to remapping. This was documented in a recent series of training studies which measured the vertical SNARC before, during and after a number entry task (for details, see Fischer, 2012). Specifically, healthy adults were first classified into two groups according to their pre-experimental vertical SNARC. Those who showed the tropic association (the majority) were required to enter digits on a numerical keypad with the telephone mapping (small numbers above large numbers), while those few participants who showed the reverse pre-experimental association (perhaps due to recent telephone use) had to enter digits on a numerical keyboard that exhibits the tropic mapping (small numbers below large numbers); in other words, both groups had to unlearn their initial SNARC. Consistent with predictions derived from our hierarchical view of tropism, embodiment and situatedness, the tropic mapping was harder to unlearn than the reverse mapping.

Now consider embodied representations of number magnitude. These should be sensitive to an individual’s learning history and, in particular, to their sensory-motor experiences with number magnitudes. Finger counting is a good example of embodied numerical cognition. Most people acquire number concepts through finger counting in childhood, and there are systematic culture-specific preferences for starting to count on either the left or right hand (Lindemann et al., 2011). Interestingly, these counting habits influence numerical cognition even in adulthood (for review, see Fischer & Brugger, 2011). For example, passive viewing of small numbers activates the right-hand motor cortex in those adults who prefer to start counting on their left hand (Tschentscher et al., 2012). The SNARC effect is also modulated by starting hand (Fischer, 2008) and adults' number comparison speed depends on whether the numbers are signalled with one or two hands (Domahs et al., 2010).

The embodied level of (offline) knowledge representation is where individual differences might come into play, from either one's sensory impairments (e.g., blindness, deafness, or deafferentation) or one's motoric constraints (e.g., extreme height, weight, or arthritis) or both (e.g., an amputation or neuropathy). For a recent review of individual differences in embodied cognition, see Casasanto (2011) or Fischer & Keehner (2012).

Finally, consider the situated spatial representation of numbers. This level of knowledge representation (or accessibility) is characterized by extremely flexible performance biases that indicate rapid changes in spatial-numerical mappings. One such example is the effect of head orientation on the average magnitude of randomly generated numbers (Lötscher et al., 2008): When turning their head to the left, adults generate more small numbers, and when turning their head to the right they generate more large numbers. However, in speakers of Hebrew, this typical left-right association (small numbers on the left and larger numbers on the right) is eliminated immediately after a single Hebrew word (read from right to left) is presented (see Fischer et al., 2009). Results such as these predict an extremely steep learning curve for situated representations in remapping experiments. Embodied representations should require longer training, and tropic representations the longest—the latter two are associated with increasingly stable representations of numerosity.

Perspective taking: A case for the offline-online distinction

Non-symbolic theories of cognition have been motivated in part by the observation that humans (and other species) use their own body repertoire to implicitly simulate what they perceive in others (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese, 2007). Recently, Kessler and Thomson (2010) showed that adopting someone else's visuo-spatial perspective consciously and deliberately requires an embodied mental simulation, suggesting a connection between implicit (automatic) self-other mappings (Kessler & Miellet, in press; Meltzoff & Moore, 1997; Reed & Farah, 1995) and conscious representations of others' mental states (Hamilton, Brindley, & Frith, 2009; Surtees, Noordzij, & Apperly, 2012). However, different forms or levels of visuo-spatial perspective taking differ with respect to the online vs. offline contributions of embodied and situated features (Kessler & Rutherford, 2010).

Developmental and comparative psychologists have suggested two levels of perspective taking (Flavell, Everett, Croft, & Flavell, 1981; Moll & Tomasello, 2006; Tomasello, Carpenter, Call, Behne, & Moll, 2005). Level-1 perspective taking (PT) involves, for example, tracking whether or not an object is visible to another perceiver. Kessler and Rutherford (2010) showed that such a judgment is equivalent to verbally determining whether a target is "in front of" or "behind" an occluding object from another perspective (Fig. 1). By contrast, Level-2 PT involves understanding how the visual world appears to another perceiver (Flavell et al., 1981). Imagine telling a friend that she has an eyelash on her left cheek. This requires determining "left" and "right" from your friend's perspective independently of your own viewpoint (see Figure 1).

======insert Figure 1 about here======

Both forms of PT result in cognitive representations of other people's views of the world that are strongly determined by the context of the specific situation and can be related to specific features of the human perceptual apparatus and body (Kessler & Rutherford, 2010). However, the body's involvement in achieving each representational level online essentially differs. It was shown that only Level-2 PT involves an embodied transformation by means of a simulated rotation of the observer's body schema (Kessler & Rutherford, 2010; Kessler & Thomson, 2010; see Fig. 1). Level-1 PT is determined differently – in relation to the line of sight of the other person (cf. Michelon & Zacks, 2006) without a simulated body rotation (Fig. 1). In agreement with Grabowski (1999), Kessler & Rutherford (2010) concluded that "in front"/"behind" relate to asymmetries of the human body, where the eyes and the face define the front, while "left"/"right" relate to its symmetrical sides. As a consequence, the front of the egocentric perspective or any other perspective can be easily determined. This is also the case for objects, where the canonical use can define an intrinsic front and back (e.g. cars, Grabowski, 1999; Levelt, 1996). A perceptible front automatically implies a line-of-sight and the "in front of" direction, while "behind" can be directly derived as the opposite pole. According to our representational hierarchy, the stored offline concepts of "in front" and "behind" therefore contain embodied elements that relate to specific body features independent of a specific situational context.

Crucially, however, the (typical) human body is visually symmetrical in the left/right dimension. Thus, no features are available for extracting and storing offline embodied representations for "left" and. "right" – this would be different if humans only possessed one lateralized arm for instance. For remembering the egocentric left and right, various online strategies are possible and a few might involve mental simulation of handedness (e.g. “The hand I use for writing is on the “right” side of my body”). Due to the lack of visually distinguishable features, another’s left or right must be determined by projecting the egocentric left/right onto their body and perspective (Kessler & Wang, 2012). This requires an online simulation of a body rotation that is realistic and deeply embodied but specific to a given situation: The amount and direction of simulated body rotation depends on the spatial orientation of the observer in relation to the target perspective (Fig. 1). Thus, embodiment only plays a role online when movement simulation is engaged.

A clear dissociation between the two levels of perspective taking (and associated linguistic expressions) reveals a relational distinction between situated and embodied representational elements. The long-term representations of “in front” and ”behind” contain offline embodied elements (e.g. gaze, line-of-sight). This also implies that the online representations (and the associated line-of-sight) do not necessitate such a realistic simulation process as the one observed for “left” versus “right”. However, decoding another person’s gaze could be regarded as a form of online embodiment in its own right, given that processes of implicit motor resonance have indeed been reported for gaze perception (for a review Frischen, Bayliss, & Tipper, 2007; Grosbras, Laird, & Paus, 2005; Wallentin, Roepstorff, & Burgess, 2008). Nevertheless, such a form of online embodiment is assumed to be more implicit than an explicit embodied simulation. By contrast, “left” versus “right” are embodied in form of online simulated body schema rotations; their long-term (offline) representations are proposed to merely ‘point’ to the generic neural algorithms that achieve a situated representation by embodied means (i.e. a simulated body rotation).

The diagnostic features proposed in the current paper suggest three main conclusions. First, the mental body schema rotation during Level-2 PT for determining “left” versus “right” entails a more elaborate online simulation process than Level-1 PT associated with “in front” versus “behind”. Second, for “left” versus “right”, one can predict activation in body-related brain areas that should also reflect the required amount of body schema transformation (i.e. angular disparity). Supporting evidence is indeed accumulating (e.g. Lambrey, Doeller, Berthoz, & Burgess, 2012; Wraga, Shephard, Church, Inati, & Kosslyn, 2005; Zacks & Michelon, 2005). Third, the dimensional polarities of “left” versus “right” should be easier to reverse through re-training than “in front” versus “behind”. While the latter is still an open empirical question, error data showing increased confusion with “left” versus “right” compared to “in front” versus “behind” provide some supporting evidence (Kessler & Rutherford, 2010).

As mentioned before, the body asymmetries that lead to different embodied and situated properties for left/right vs. in-front/behind along the online/offline distinction, including predictions about efforts for retraining can be generalised to other concepts that are mapped on the different body axes. Concepts of valence and time that are related to the font-back axes (and even more so to the body- and gravity-based top-bottom axes) would be harder to re-train and would require less online simulation than concepts related to the more symmetrical left-right axes that could only rely on the weaker handedness feature for long-term representations.

Conclusions

In this paper, we presented a novel ontological framework, called TEST, which suggests independent diagnostics for the presence of tropic, situated, and embodied features of simulated modal representations. Our approach is particularly novel by emphasising the interaction between embodied, situated, and tropic aspects for online as well as offline representations. The latter highlights the importance of the learning history for determining how online tropic, situated and embodied aspects of the world transpire into the offline core of representations. We also discussed a number of examples of experimental effects corresponding to the distinct tropic, embodied, and situated features of simulated representations from the research on abstract language, number processing, and perspective taking.

Overall, our proposal makes a step towards unifying embodied theories of cognition by deriving diagnostic features from the proposed relationships between world-, body-, and context-related effects. Prominently, these include (a) the requirements for, and the “realism” or “depth” of, the involved cognitive simulations; (b) the steepness of learning and re-training gradients of specific features in long-term representations; and (c) the degree to which a particular conceptual representation depends on the online constraints provided by the mental representations of the body, the situation, and the outside world. These diagnostic features lead to concrete hypotheses, e.g., regarding the situated and/or embodied reversal of long-term effects (e.g. for valence). We conclude that it is beneficial to distinguish between representational constraints imposed by the physical world, the body, and the situational context. This certainly allows for more specific predictions than the conjecture that bodies, situational contexts, and the world are all related somehow.

References

Barsalou, L.W. (2008). Grounded Cognition. *Annual Review of Psychology*, 59, 617–645.

Barsalou, L.W. (2009). Simulation, situated conceptualization, and prediction. *Philosophical Transactions of the Royal Society: Biological Sciences,* 364, 1281-1289.

Barsalou, L.W. (2010). Grounded cognition: Past, present, and future. *Topics in Cognitive Science,* 2, 716-724.

Barsalou, L.W., & Wiemer-Hastings, K. (2005). Situating abstract concepts. In D. Pecher and R. Zwaan (Eds.), *Grounding cognition: The role of perception and action in memory, language, and thought* (pp. 129-163). New York: Cambridge University Press.

Bergen, B.K., & Lau, T.T.C. (2012). Writing direction affects how people map space onto time. *Frontiers in Cultural Psychology,* 3:109.

Boroditsky, L. (2000). Metaphoric Structuring: Understanding time through spatial metaphors.*Cognition,* 75(1), 1-28.

Boroditsky, L. (2001). Does language shape thought? English and Mandarin speakers' conceptions of time. *Cognitive Psychology,* 43(1), 1-22.

Boroditsky, L. (2011). How Languages Construct Time. In S. Dehaene & E.M. Brannon (Eds.,) *Space, time, and number in the brain: Searching for the foundations of mathematical thought.* (pp. 333-341). Elsevier.

Boroditsky, L., Fuhrman, O., & McCormick, K. (2011). Do English and Mandarin speakers think differently about time? *Cognition,* 118(1), 123-129.

Boroditsky, L., & Gaby, A. (2010). Remembrances of Times East: Absolute Spatial Representations of Time in an Australian Aboriginal Community. *Psychological Science*, 21(11), 1635-1639.

Brookshire, G., & Casasanto, D. (2011). Motivation and motor control: Hemispheric specialization for motivation reverses with handedness. In L. Carlson, C. Hölscher, & T. Shipley (Eds.), *Proceedings of the 33rd Annual Conference of the Cognitive Science Society* (pp. 2610–2615). Austin, TX: Cognitive Science Society.

Brysbaert, M., Fias, W., & Noel, M.-P. (1998). The Whorfian hypothesis and numerical cognition: Is 'twenty-four' processed in the same way as 'four-and-twenty'? *Cognition,* 66, 51-77.

Cacciari, C., Bolognini, N., Senna, I., Pellicciari, M.C., Miniussi, C., & Papagno, C. (2011). Literal, fictive and metaphorical motion sentences preserve the motion component of the verb: A TMS study. *Brain and Language,* 119(3), 149-157.

Cangelosi A. (2006). The grounding and sharing of symbols. *Pragmatics and Cognition,* 14(2), 275-285.

Cangelosi, A., Greco, A., & Harnad, S. (2002). Symbol Grounding and the symbolic theft hypothesis. In Cangelosi, A., & Parisi, D. (Eds.), *Simulating the Evolution of Language.* (pp. 191-210). London: Springer.

Casasanto, D. (2009). Embodiment of Abstract Concepts: Good and bad in right- and left-handers. *Journal of Experimental Psychology: General,* 138(3), 351-367.

Casasanto, D. (2011). Different Bodies, Different Minds: The body-specificity of language and thought. *Current Directions in Psychological Science,* 20(6), 378–383.

Casasanto, D., & Chrysikou, E.G. (2011). When Left is "Right": Motor fluency shapes abstract concepts. *Psychological Science,* 22(4), 419-422.

Chatterjee, A. (2010). Disembodying Cognition. *Language and Cognition,* 2(1), 79-116.

Clark, A. (in press). Whatever Next? Predictive Brains, Situated Agents, and the Future of Cognitive Science. *Behavioral and Brain Sciences.*

Colder, B. (2011). Emulation as an integrating principle for cognition. *Frontiers in Human Neuroscience,* 5:54.

Crawford, L.E. (2009). Conceptual metaphors of affect. *Emotion Review,* 1(2), 129-139.

Dalecki, M. Sebastian D., Steinberg, F. (2013). Mental rotation of a letter, hand and complex scene in microgravity. *Neuroscience Letters*, 533, 55-59.

di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V., & Rizzolatti, G. (1992). Understanding motor events: a neurophysiological study. *Exp Brain Res*, 91, 176-180.

Dove, G. (2011). On the need for embodied and dis-embodied cognition. *Frontiers in Psychology,* 1:242.

Fazio, P., Cantagallo, A., Craighero, L., D'Ausilio, A., Roy, A.C., Pozzo, T., Calzolari, F., Granieri, E., & Fadiga, L. (2009). Encoding of human action in Broca's area. *Brain,* 132, 1980-1988.

Flavell, J.H., Everett, B.A., Croft, K., & Flavell, E.R. (1981). Young Childrens Knowledge About Visual-Perception - Further Evidence for the Level 1-Level 2 Distinction. *Developmental Psychology*, 17, 99-103.

Fischer, M. H., Riello, M., Giordano, B.L., & Rusconi, E. (in press). Singing numbers ...in cognitive space. *Topics in Cognitive Sciences.*

Fischer, M.H. (2012). The spatial mapping of numbers – its origin and flexibility. In Coello, Y., & Bartolo, A. (Eds.), *Language and action in cognitive neurosciences*. London: Psychology Press. (in press).

Fischer, M.H., & Brugger, P. (2011). When digits help digits: Spatial-numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology,* doi: 10.3389/fpsyg.2011.00260.

Fischer, M.H., Shaki, S., & Cruise, A. (2009). It takes only one word to quash the SNARC. *Experimental Psychology,* 56(5), 361-366.

Fischer, M.H., & Keehner, M.M. (2012). Unusual Bodies, Uncommon Behaviors: Embodied Cognition and Individual Differences in Spatial Tasks. *Special Issue of Spatial Cognition and Computation.* (forthcoming).

Fodor, J.A. (1983). *Modularity of Mind,* Cambridge, Mass.: MIT Press.

Frischen, A., Bayliss, A.P., & Tipper, S.P. (2007). Gaze cueing of attention: visual attention, social cognition, and individual differences. *Psychol Bull*, 133, 694-724.

Fuhrman, O., & Boroditsky, L. (2010). Cross-Cultural Differences in Mental Representations of Time: Evidence from an Implicit Non-Linguistic Task. *Cognitive Science*, 34, 1430-1151.

Gallese V. (2005). Embodied simulation: from neurons to phenomenal experience. *Phenomenology and the Cognitive Sciences,* 4, 23–48.

Gallese, V. (2007). Before and below 'theory of mind': embodied simulation and the neural correlates of social cognition. *Philosophical Transactions of Royal Society B: Biological Sciences*, 362, 659-669.

Gallese, V., & Lakoff, G. (2005). The Brain's concepts: the role of the Sensory-motor system in conceptual knowledge. *Cognitive Neuropsychology,* 22(3-4), 455-479.

Garzon, P.C., & Kejzer, F. (2011). Plants: Adaptive behavior, root-brains, and minimal cognition. *Adaptive Behaviour,* 19(3), 155-171.

Gianelli, C., Scorolli, C., & Borghi, A. (in press). Acting in perspective: the role of body and language as social tools. *Psychological Research,* 1-13.

Gilead M., Liberman N., & Maril, A. (2012). Construing counterfactual worlds: The role of abstraction, *European Journal Of Social Psychology,* 42(3), 391-397.

Glenberg, A.M., & Gallese, V. (in press). Action-based language: A theory of language acquisition production and comprehension. *Cortex.*

Glenberg, A.M., & Kaschak, M.P. (2002). Grounding language in action. *Psychonomic Bulletin & Review,* 9(3), 558-565.

Glenberg, A.M., Sato, M., Cattaneo, L., Riggio, L., Palumbo, D., & Buccino, G. (2008). Processing abstract language modulates motor system activity. *The Quarterly Journal of Experimental Psychology,* 61(6), 905-919.

Grabowski, J. (1999). A uniform anthropomorphological approach to the human conception of dimensional relations. *Spatial Cognition and Computation*, 1, 349-363.

Grosbras, M.N., Laird, A.R., & Paus, T. (2005). Cortical regions involved in eye movements, shifts of attention, and gaze perception. *Human Brain Mapping*, 25, 140-154.

Guerra-Filho, G., & Aloimonos, Y. (2012). The syntax of human actions and interactions, *Journal of Neurolinguistics*, 25(5), 500-514.

Hamilton, A.F.D., Brindley, R., & Frith, U. (2009). Visual perspective taking impairment in children with autistic spectrum disorder. *Cognition*, 113, 37-44.

Hauk, O., Johnsrude, I., & Pulvermuller, F. (2004). Somatotopic representation of action words in human motor and premotor cortex. *Neuron,* 41, 301–307.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relation between physical and semantic size in comparison tasks. *Memory and Cognition,* 10, 389-395.

Hesslow, G. (2012). The current status of the simulation theory of cognition. *Brain Research,* 1428, 71-79.

Ito, Y., & Hatta, T. (2004). Spatial structure of quantitative representation of numbers: Evidence from the SNARC effect. *Memory & Cognition,* 32, 662-673.

Jasmin, K., & Casasanto, D. (2012). The QWERTY Effect: How typing shapes the meanings of words. *Psychonomic Bulletin and Review*, doi: 10.3758/s13423-012-0229-7.

Johnson, M. (2007). *The Meaning of the Body: Aesthetics of Human Understanding,* Chicago: University of Chicago Press. pp. 86-110.

Karban, R. (2008). Plant behaviour and communication. *Ecology Letters,* 11, 727-739.

Kemmerer, D. (2012). The Cross-Linguistic Prevalence of SOV and SVO Word Orders Reflects the Sequential and Hierarchical Representation of Action in Broca's Area. *Language and Linguistic Compass,* 6(1), 50-66.

Kessler, K., & Rutherford, H. (2010). The two forms of Visuo-Spatial Perspective Taking are differently embodied and subserve different spatial prepositions. *Frontiers in Psychology*, 1, doi: 10.3389/fpsyg.2010.00213.

Kessler, K., & Thomson, L.A. (2010). The embodied nature of spatial perspective taking: embodied transformation versus sensorimotor interference. *Cognition*, 114, 72-88.

Kessler, K., & Miellet, S. (in press). Perceiving Conspecifics as Integrated Body-Gestalts Is an Embodied Process. *J Exp Psychol Gen.*

Kessler, K., & Wang, H.F. (2012). Spatial perspective taking is an embodied process, but not for everyone in the same way: Differences predicted by sex and social skills score. *Spatial Cognition and Computation,* 12, 133-158.

Kiss, J.Z. (2006). Up, down, and all around: How plants sense and respond to environmental stimuli. *Proceedings of the National Academy of Science of the United States of America,* 103(4), 829–830.

Lakens, D. (2012). Polarity Correspondence in Metaphor Congruency Effects: Structural Overlap Predicts Categorization Times for Bi-Polar Concepts Presented in Vertical Space. *Journal of Experimental Psychology: Learning, Memory, and Cognition,* 38, 726-723.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by.* Chicago: University of Chicago Press.

Lambrey, S., Doeller, C., Berthoz, A., & Burgess, N. (2011). Imagining Being Somewhere Else: Neural Basis of Changing Perspective in Space. *Cereb Cortex*.

Levelt, W.J.M. (1996). Perspective taking and ellipsis in spatial descriptions. In: Bloom, P., Peterson, M.A., Nadel, L., Garret, M.F. (Eds.), *Language and Space*. A Bradford Book, Cambridge (Mass.), pp. 77-108.

Lindemann, O., Alipour, A., & Fischer, M. H. (2011). Finger Counting Habits in Middle-Eastern and Western Individuals: An Online Survey. *Journal of Cross-Cultural Psychology, 42*, 566-578

Loetscher, T., Schwarz, U., Schubiger, M., & Brugger, P. (2008). Head turns bias the brain's random number generator. *Current Biology,* 18(2), R60-R62.

Louwerse, M.M., & Connell, L. (2011). A Taste of words: Linguistic context and perceptual simulation predict the modality of words. *Cognitive Science,* 35, 381-398.

Markman, A.B., & Brendl, C.M. (2005). Constraining theories of embodied cognition. *Psychological Science,* 16(1), 6-10.

Meier, B.P., & Robinson, M.D. (2004). Why the Sunny Side Is Up : Associations Between Affect and Vertical Position. *Psychological Science,* 15(4), 243-247.

Meier, B.P., & Robinson, M.D. (2006). Does “feeling down” mean seeing down? Depressive symptoms and vertical selective attention. *Journal of Research in Personality,* 40, 451–461.

Meier, B.P., Schnall, S., Schwartz, N., & Bargh, J.A. (in press). Embodiment in social psychology. *Topics in Cognitive Science.*

Meltzoff, A.N., & Moore, M.K. (1997). Explaining facial imitation: A theoretical model. *Early Development & Parenting*, 6, 179-192.

Michelon, P., & Zacks, J.M. (2006). Two kinds of visual perspective taking. *Percept Psychophys*, 68, 327-337.

Moeller, S. K., Robinson, M. D., & Zabelina, D. L. (2008). Personality dominance and preferential use of the vertical dimension of space: Evidence from spatial attention paradigms. *Psychological Science,* 19, 355–361.

Moll, H., & Tomasello, M. (2006). Level I perspective-taking at 24 months of age. *Brit J Dev Psychol*, 24, 603-613.

Moulton, S.T., & Kosslyn, S.M. (2009). Imagining predictions: mental imagery as mental emulation. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 364, 1273-1280.

Myachykov, A., Platenburg, W.P.A., & Fischer, M.H. (2009). Non-abstractness as mental simulation in the representation of number. *Behavioral And Brain Sciences,* 32(3/4), 343-344.

Newell, A., Simon, H. A. (1972). *Human Problem Solving.* Englewood Cliffs, NJ: Prentice-Hall.

Nuerk, H.-C., Willmes, K., & Fischer, M. H. (2011). Multi-digit number processing. *Special Issue of Zeitschrift für Psychologie/Journal of Psychology.* Hogrefe Publishing. ISSN: 2190-8370.

Ortiz, M.J. (2011). Primary metaphors and monomodal visual metaphors. *Journal of Pragmatics,* 43, 1568–1580.

Pezzulo, G, Barsalou, L.W., Cangelosi, A., Fischer, M.H., McRae, K., & Spivey, M.J. (2011). The mechanics of embodiment: a dialog on embodiment and computational modelling, *Frontiers in Psychology,* doi: 10.3389/fpsyg.2011.00005

Pickering, M.J., & Garrod, S. (2009). Prediction and embodiment in dialogue. *European Journal of Social Psychology,* 39, 1162-1168.

Poff, K.L., Janoudi, A.K., Rosen, E.S., Orbovid, V., Konjevic, R., Fortin, M.C., & Scott, T.K. (1994). The physiology of tropisms. In E.M. Meyerowitz, & C.R. Sometville (Eds), *Arabidopsis.* (pp. 639-664). New York: Cold Spring Harbor Laboratory Press.

Pulvermuller, F., & Fadiga, L. (2010). Active perception: sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience,* 11, 351-360.

Pylyshyn, Z.W. (2009). Perception, Representation and the World: The FINST that binds. In D. Dedrick, & L.M. Trick (Eds.), *Computation, Cognition, & Pylyshyn*. (pp. 3-46). Cambridge, MA: MIT Press.

Reed, C.L., & Farah, M.J. (1995). The Psychological Reality of the Body Schema - a Test with Normal Participants. *Journal of Experimental Psychology-Human Perception and Performance*, 21, 334-343.

Retz-Schmidt, G. (1988). Various views on spatial prepositions. *AI Magazine*, 9, 95-105.

Robinson, M.D., Zabelina, D.L., Ode, S., & Moeller, S.K. (2008). The vertical nature of dominance-submission: Individual differences in vertical attention. *Journal of Research in Personality,* 42, 933-948.

Rusconi, E., Kwan, B., Giordano, B., Umiltà, C., & Butterworth, B. (2005). Spatial representation of pitch height: the SMARC effect. *Cognition,* 99, 113-129.

Schwarz, W., & Keus, I. (2004). Moving the eyes along the mental number line: Comparing SNARC effects with manual and saccadic responses. *Perception & Psychophysics,* 66, 651-664.

Shaki, S., & Fischer, M. H. (2012). Multiple spatial mappings in numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance* (in press).

Surtees, A.D.R., Noordzij, M.L., & Apperly, I.A. (2012). Sometimes Losing Your Self in Space: Children's and Adults' Spontaneous Use of Multiple Spatial Reference Frames. *Developmental Psychology*, 48, 185-191.

Tschentscher, N., Hauk, O., Fischer, M. H., & Pülvermuller, F. (2012). You can count on the motor cortex: fMRI reveals embodied number processing. *NeuroImage,* 59, 3139-3148.

Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: the origins of cultural cognition. *Behav Brain Sci*, 28, 675-691; discussion 691-735.

Tucker, D.M. (2001). Motivated anatomy: A core-and-shell model of corticolimbic architecture. In G. Gainotti, (Ed.), *Handbook of neuropsychology* (2nd edn, Vol. 5: *Emotional behavior and its disorders,* (pp. 125–160). Amsterdam: Elsevier.

Tulving, E. (1983). Elements of Episodic Memory, Oxford University Press: New York.

Wallentin, M., Roepstorff, A., & Burgess, N. (2008). Frontal eye fields involved in shifting frame of reference within working memory for scenes. *Neuropsychologia*, 46, 399-408.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin and Review,* 9, 625–636.

Wood, G., Nuerk, H.-C., Willmes, K., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly,* 50(4), 489-525.

Wraga, M., Shephard, J.M., Church, J.A., Inati, S., & Kosslyn, S.M. (2005). Imagined rotations of self versus objects: an fMRI study. *Neuropsychologia*, 43, 1351-1361.

Zacks, J.M., & Michelon, P. (2005). Transformations of visuospatial images. *Behav Cogn Neurosci Rev*, 4, 96-118.

Zwaan, R.A., & Taylor, L.J. (2006). Seeing, acting, understanding: Motor resonance in language comprehension. *Journal of Experimental Psychology: General,* 135, 1–11.

Tables and figures

Table 1: Representational components within the TEST theory.

Component	**Domain**	**Stability**
Tropic	Physical world	Stable
Embodied	Body	Moderately stable
Situated	Context	Less stable

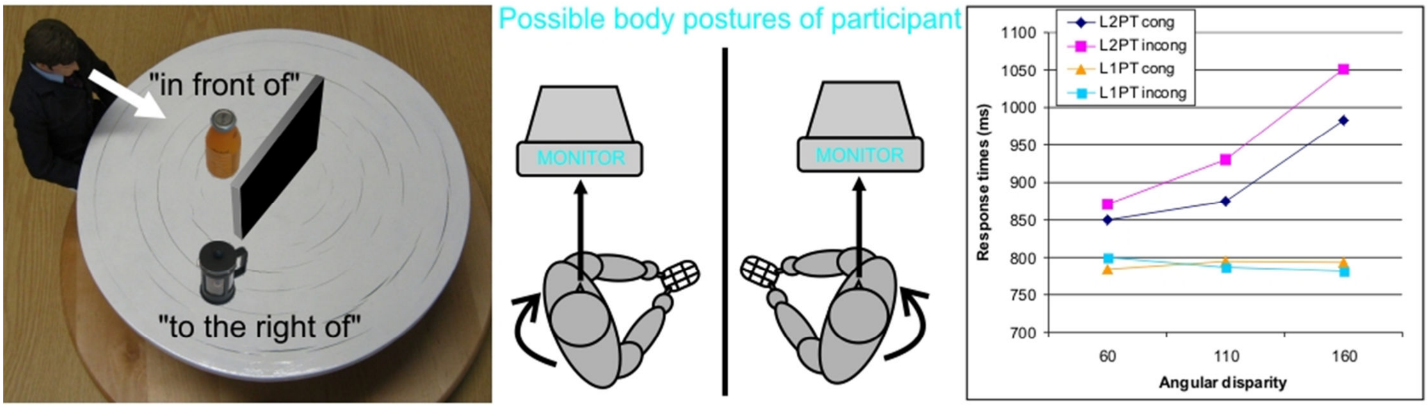

Figure 1: Left shows examples of “in front of”, requiring Level-1 perspective taking (L1PT in the results graph) and of “to the right of”, requiring Level-2 perspective taking (L2PT). The stimuli in Kessler and Rutherford (2010) employed the same table and avatar as shown here, but slightly different targets (coloured hemispheres). Middle shows the two possible body posture that participants were instructed to adopt before each trial in Kessler and Rutherford (2010; also in Kessler & Thomson, 2010). The postures could be either congruent or incongruent with the direction in which the avatar was positioned. Here, the left posture is turned towards the avatar shown in the left picture, giving an example for the “congruent” condition, while the right posture is turned away, giving an example for the “incongruent” condition. Right shows a result graph for response times in ms (cf. Kessler & Rutherford, 2010). L2PT (“left”/”right”) was significantly affected by angular disparity and posture congruence (congruent faster than incongruent, particularly at 110 and 160 deg disparity). No effects were observed for L1PT (“in front”/”behind”).