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Review

Mental number space in three dimensions

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ABSTRACT

A large number of experimental findings from neuroscience and experimental psychology demonstrated interactions between spatial cognition and numerical cognition. In particular, many researchers posited a horizontal mental number line, where small numbers are thought of as being to the left of larger numbers. This review synthesizes work on the mental association between space and number, indicating the existence of multiple spatial mappings: recent research has found associations between number and vertical space, as well as associations between number and near/far space. We discuss number space in three dimensions with an eye on potential origins of the different number mappings, and how these number mappings fit in with our current knowledge of brain organization and brain-culture interactions. We derive novel predictions and show how this research fits into a general view of cognition as embodied, grounded and situated.

Contents

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1. Spatial representation of numbers

Understanding the nature of knowledge representation in the brain is perhaps the most fundamental challenge for cognitive scientists and neuroscientists. The domain of numerical knowledge lends itself to investigating this topic because of its universality and practical relevance. The current review provides an update on recent insights into the cognitive and neural representation of number knowledge, with a focus on the embodied, cultural and situated nature of such knowledge.

Time and time again, research on the mental representation of numbers has revealed a close connection between numerical and spatial cognition. The neural substrate for this close interaction is thought to be the bilateral intra-parietal sulcus which implements both spatial and numerical processing (Hubbard et al., 2005; Kaufmann et al., 2008; Pinel et al., 2004; Winter et al., 2015). A key behavioral finding that documents the close link between space and numbers is the Spatial–Numerical Association of Response Code (SNARC) effect. When asked to quickly classify single digits by their parity ("is this number odd or even?"), healthy adults typically respond more quickly to smaller numbers with a left side button, and more quickly to larger numbers, with a right side button (Dehaene et al., 1993). This finding has now been replicated and extended hundreds of times (Wood et al., 2008; Fischer and Shaki, 2014). A common interpretation of the SNARC effect is that people maintain a horizontally oriented "mental number line," where small numbers are represented toward the left of larger numbers. Although Dehaene and colleagues were not the first to propose a spatial representation for numbers (e.g., Galton, 1880a,b; Seron et al., 1992; Restle, 1970), the SNARC effect has greatly popularized this idea.

As will be reviewed below, the spatial association of numbers extends from the horizontal into the vertical and radial dimensions (see Fig. 1). We discuss the origin of and the relation among these multiple spatial–numerical mappings. All these mappings for thinking about numbers appear to stem from sensory-motor interactions with the world around us. Our review, therefore, emphasizes the value of taking an embodied, grounded and situated approach to studying knowledge representations in the human mind.

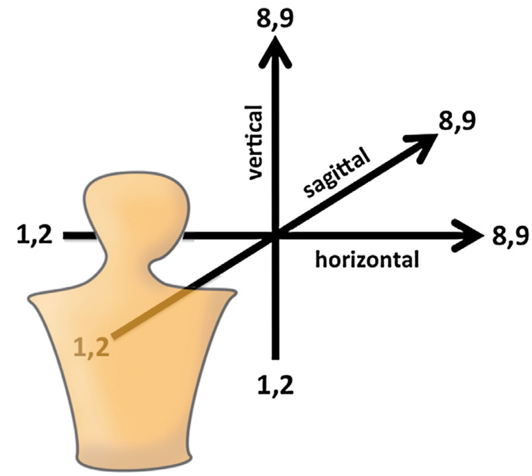

Fig. 1. Spatial–numerical associations along three dimensions.

2. Empirical evidence for 3-dimensional mental magnitudes

2.1. Horizontal spatial–numerical associations

The original SNARC study (Dehaene et al., 1993) reported a behavioral interaction between numerical magnitude and horizontally arranged response buttons. Similar interactions have been observed across a wide range of measures and body parts, including foot movements (Schwarz and Müller, 2006), pointing movements (Fischer, 2003b; Fischer and Campens, 2009; Chapman et al., 2014; Song and Nakayama, 2008), free hand writing (Perrone et al., 2010), and eye movements (Schwarz and Keus, 2004; Loetscher et al., 2010; Ruiz Fernández et al., 2011; Fischer et al., 2004). Many studies have also reported an "attentional SNARC effect", in which smaller numbers shift attention to left visual space, and larger numbers, to right visual space, even when no lateralized effectors or movements are involved (Fischer et al., 2003; Dodd et al., 2008; Galfano et al., 2006; Goffaux et al., 2012; Salillas et al., 2008; van Dijck et al., 2014; for recent discussion, see Zanolie and Pecher, 2014, and Fischer and Knops, 2014). Across all these studies, left space is reliably associated with smaller magnitudes, and right space, with larger magnitudes.

Random number generation (RNG) tasks have also been used to explore spatial–numerical associations. Here, participants are asked to call out a sequence of numbers as randomly as possible while performing a spatial task. When doing this while simultaneously performing horizontal head movements, they generate relatively larger numbers when looking to the right, and smaller numbers when looking to the left (Loetscher et al., 2008a). Similarly, when participants perform random number generation while walking, they produce larger numbers before taking an instructed right turn instead of an instructed left turn, and they spontaneously turn left more often than right when they say small compared to large numbers (Shaki and Fischer, 2014). Even without explicit movements of the limbs, horizontal eye position predicts the magnitude of the next number that a participant generates in a sequence (Loetscher et al., 2010). Finally, observing eyes gazing in a particular direction also affects number generation. When participants observe others gazing toward the left, they generate smaller numbers than when they observe eyes looking toward the right (Grade et al., 2013).

Converging evidence for a horizontal spatial association of numbers comes from neurological patients who suffer from hemispatial neglect, an impairment that results in the loss of the cognitive representation of space contralateral to the side of their brain lesion (Karnath, 2012). When patients with right parietal damage and left neglect are asked, "What number is half-way between 2 and 6?" they tend to exhibit a bias toward larger numbers, specifically, they erroneously respond "5" instead of "4" (Zorzi et al., 2002). This finding is taken to suggest that left neglect either abolishes the representation of small (=left-sided) numbers, or at least biases attention toward the right (Vuilleumier et al., 2004; Umiltà et al., 2009; Zorzi et al., 2006). A similar bias to neglect small numbers can be induced in healthy adults with transcranial magnetic stimulation over right posterior parietal cortex (Göbel et al., 2006).

Finally, horizontal number-space associations have not just been found in simple number processing. They have also been observed in mental arithmetic (Pinhas and Fischer, 2008; McCrink et al., 2007; Knops et al., 2014, 2009a,b; Masson and Pesenti, 2014; Pinhas et al., 2014; Wiemers et al., 2014; Werner and Raab, 2014; Marghetis et al., 2014; Klein et al., 2014). For example, when participants indicate the outcome of addition and subtraction problems by pointing to a visually presented horizontal line that represents ordered magnitudes, they systematically point more rightward when solving addition problems and more leftward when solving subtraction problems (Pinhas et al., 2014). Documenting the opposite direction of this associative link, directional physical activities (Wiemers et al., 2014; Werner and Raab, 2014) and even processing left- vs. right-branching syntactic structures (Scheepers and Sturt, 2014) can induce corresponding arithmetic biases.

2.2. Vertical spatial–numerical associations

Relatively little attention has been given to associations between numbers and vertical space, perhaps because early research, including the original SNARC study (Dehaene et al., 1993), emphasized horizontal associations. A primary source of evidence for vertical spatial–numerical mappings comes from the RNG task: When participants generate numbers while being moved upward by a body-lifting device, they tend to generate larger numbers than when being moved downward (Hartmann et al., 2012). Similarly, when participants generate numbers while turning their head up and down, they tend to generate higher numbers when looking up (Winter and Matlock, 2013). Moreover, vertical eye movements predict numerical magnitude in the RNG task (Loetscher et al., 2010). Upward eye movements are followed by relatively larger numbers, downward eye movements by relatively smaller ones. Consistent with this, when asked to respond with eye movements rather than hand movements, participants respond faster to larger numbers when looking upward (i.e., vertical SNARC; Schwarz and Keus, 2004). However, another study found a horizontal effect, but not a vertical one (Loetscher et al., 2008a). In that case, participants verbally responded to spoken questions such as "which number is halfway between 4 and 8?". The eyes moved left when the interval was named in decreasing numerical order (e.g., 8–4), and right when the interval was named in increasing order (e.g., 4–8), but the eyes did not move up or down in a systematic fashion.

More closely mirroring the classic SNARC paradigm, Hartmann et al. (2014) used a setup with two buttons on top of each other. Participants made parity judgments faster in response to larger numbers with the "up" button, and to smaller numbers with the "down" button, regardless of whether the left hand was assigned the lower key or the upper key. A related study with a similar vertical setup of response keys (Sell and Kaschak, 2012) showed that reading sentences such as *More runs were being scored this game* leads to quicker upward directed responses; in contrast, reading *Fewer runs were being scored this game* leads to quicker downward directed responses. A similar result was obtained with Chinese words associated with the concepts "more" and "less" (Guan et al., 2013). In this case, ERP measurements revealed a stronger N400 component when there was a mismatch between response and implied quantity (i.e., more/down and less/up).

There are also "attentional SNARC" effects along the vertical axis. Specifically, reading sentences such as *The old man had 2 books in his book case* (which implies a small quantity), facilitates the detection of a visual target positioned relatively low on a computer screen. On the other hand, reading sentences such as *The old man read 2 books a day* (which implies a comparatively larger quantity) facilitates detection of a high target (Pecher and Boot, 2011). Moreover, processing small numbers facilitates the subsequent processing of words associated with low space, such as *foot*, whereas processing large numbers facilitates words associated with high space, such as *bird* (Lachmair et al., 2014).

Just as with the horizontal dimension, vertical effects have been reported in relation to mental arithmetic. Participants solve addition problems faster when they are moving upward in an elevator, and subtraction problems faster when moving downward (Lugli et al., 2013). In a related study, perceiving or performing downward movements interfered with addition while perceiving or performing upward movements interfered with subtraction (Wiemers et al., 2014)[1].

Finally, research on linguistic metaphors also provides evidence for vertical space/magnitude associations. For instance, English speakers frequently make statements such as *This is a high number* or *This is a low number*, and they describe interest rates, gas prices and other abstract quantities as *rising* or *falling* (Lakoff, 1987; Lakoff and Johnson, 1980; Kövecses, 2002). Other languages, too, talk about quantities in terms of height or vertical position (e.g., German *die Preise sind gestiegen* 'prices have risen', or Italian *un numero alto* 'a high number'). Similar use of the terms *left* and *right* to express magnitudes is currently unknown.

Using vertical language to describe quantity is a productive process readily extended to other expressions such as *plummeting incomes*, *skyrocketing prices* or *ever ascending tax rates*. Such productivity is argued to show that metaphor is more than a rhetorical or poetic device. It is instead viewed as a dynamic process that structures how we think and reason (Lakoff, 1987; Lakoff and Johnson, 1980; Kövecses, 2002; Katz et al., 1998; Gibbs, 1994) and that is driven by mental simulation (Gibbs and Matlock, 2008; Gibbs, 2006). The spatial imagery involved in processing metaphoric language about quantities is revealed by an analysis of T.V. news broadcasts (Winter et al., 2014), where people were observed to perform upward directed manual gestures when talking about *high numbers*, and downward oriented ones when talking about *low numbers*. Thus, spontaneous gesturing during speaking provides yet another source of evidence for vertical associations between space and number above. The same spontaneous association between upward gestures and larger magnitudes can occur when adults are asked to point at the locations where they imagine small and large numbers in space (Fischer and Campens, 2009).

2.3. Distance-based or "sagittal" SNARC effects

The few studies that investigated vertical space/magnitude associations can be subdivided according to whether they mean the label "vertical" literally or metaphorically. We commonly talk about far as "up" and near as "down" when mentioning positions on a horizontal plane, for example, the "top" half of a page, or when saying the "N" key is below the "U" key on a keyboard (cf. Tversky, 2011). Close reading of the method sections of published work reveals that several studies interpret results in terms of truly vertical SNARC effects, when the response setup used a response pad or keyboard that was in fact positioned on a horizontal plane, i.e., a table (Ito and Hatta, 2004; Müller and Schwarz, 2007; Shaki and Fischer, 2012). These studies often find that people respond more quickly to small numbers with the nearer response button (close to the body), labeled the "low" key, and to large numbers, with the farther button, labeled the "high" key. Such effects can be found on a numeric keypad with the "2" and "8" keys as near and far responses (Holmes and Lourenco, 2011).

These distance-based effects have sometimes been called "radial" (Hartmann et al., 2014), in the sense of extending outward from the body along the horizontal plane (cf., Santens and Gevers, 2008). However, the major share of evidence comes specifically from the mid-sagittal axis, extending along the front/back axis from the body into the distance. First, there are the above-mentioned studies on "vertical" SNARC effects that positioned the response buttons along the mid-sagittal axis on a table top (Gevers et al., 2006; Ito and Hatta, 2004; Müller and Schwarz, 2007; Shaki and Fischer, 2012). Other studies supporting a critical role of the mid-sagittal axis investigated real or apparent movement along

[1] However, it should be noted that the arithmetical outcomes in Wiemers et al. (2014) were not balanced for addition and subtraction, i.e., the results of addition problems were on average 46.9, whereas the results of subtraction problems were on average 22.2. Hence, the result by Wiemers et al. (2014) could potentially be an association between space and magnitudes rather than between space and arithmetical operations (Tyler Marghetis, p.c.).

the front/back axis. When participants view optic flow patterns that induce the visual perception of backward motion, they tend to generate smaller random numbers (Seno et al., 2012). They also generate smaller numbers when physically moved backward by a body-lifting device (Hartmann et al., 2012), and larger numbers when physically moved forward. Moreover, when participants are asked to indicate their number associations freely in space, they occasionally orient them along the sagittal axis (Fischer and Campens, 2009), while others orient them along the horizontal and vertical ones. Finally, negative numbers are associated with full-body movements going backward, whereas positive numbers are associated with full-body movements going forward (Marghetis and Youngstrom, 2014)—just like negative numbers are sometimes associated with left space and positive numbers with right space (Fischer, 2003a; Shaki and Petrusic, 2005; Zhang and You, 2012).

Using the term "radial" rather than "sagittal" implies circular symmetry. Santens and Gevers (2008) gave participants a baseline key "j" from which participants had to either move to a "close" key "h" or to a "far" key "g" to classify numbers by their magnitude. Alternatively, in a rightward oriented setup, the "close" key was "k" and the far key "l." In this setup, Santens and Gevers (2008) found that small numbers were associated with "close" responses and large numbers with "far" responses—regardless of orientation. They discuss this effect in terms of a distance-based effect. This, together with the sagittal effects reported above, might suggest a "radial" effect. However, the results of Santens and Gevers (2008) could also be interpreted in terms of a number-size association (e.g., Henik and Tzelgov, 1982), where movements away from a central position indicate a larger size, just as gesturing away from the body's midpoint is used to indicate large quantities (Winter et al., 2014). Hence, the exact spatial nature (radial or sagittal?) of distance-based effects is not entirely clear at present. We will continue to use the term "sagittal" given the fact that almost all studies in support of these effects have used the front/back dimension.

3. Where do horizontal, vertical and radial SNARC effects come from?

3.1. Hebbian learning, neuronal recycling and multi-causal origins

When researchers talk about the origins of space/number associations, they often emphasize one particular origin, e.g., horizontal SNARC effects stemming from writing (Dehaene et al., 1993). Implicitly, many such discussions assume that one origin takes priority over another. For example, Pitt and Casasanto (2014) emphasize the role of counting direction (people also count from left to right), but de-emphasize the role of writing. In contrast to this, we will point out that each mapping may have convergent support from multiple sources, including brain organization, cultural practices, and the natural world. Such a multi-causal proposal is, in fact, expected based on recent insights into brain-culture interactions (Dehaene and Cohen, 2007, 2011; Anderson, 2010). For example, Anderson (2010) points out evidence suggesting that evolutionarily more recent practices (such as math) depend on comparatively larger brain networks. This includes the co-opting of brain areas previously evolved for other tasks, such as spatial cognition. In the case of spatial–numerical mappings, we will see that it is fruitful to consider numerical cognition as a "greedy" system (cf. Spivey, 2007) that develops so as to be consistent with other neural structures (such as those involved in reading) and other cultural practices (such as those involved in the visual representation of number and time).

3.2. Sources of horizontal mappings

Horizontal spatial associations are commonly taken as evidence for a spatially oriented "mental number line," according to which small numbers are placed to the left of larger numbers. This number line has sometimes been called a "cultural mental number line" (Göbel et al., 2011) because evidence reveals a close link between the orientation of the horizontal mental number line and cultural reading/writing conventions (Zebian, 2005; Shaki and Fischer, 2008; Shaki et al., 2009, 2012). Orienting spatial attention along the left-to-right axis (such as during reading) uses similar neural substrates as doing mental arithmetic (Knops et al., 2009a,b). Hence, reading and counting and calculating may share partly overlapping brain organization. However, besides this, we point out that the horizontal SNARC effect may not *only* be due to writing, but due to a confluence of cultural factors. In other words, there is convergent cultural support for the orientation of the number line.

The original SNARC study (Dehaene et al., 1993) proposed that the horizontal SNARC reflects a spillover of spatial-directional scanning habits from reading into the domain of numerical cognition. The observation that the SNARC effect begins to become reliable in children only after 3 years of schooling provided initial support for this argument (Berch et al., 1999) but more recent work has extended the range for this horizontal mapping preference well into pre-school age (Hoffmann et al., 2013; Opfer et al., 2010; Shaki et al., 2012), before most children are fluent readers and writers. Hence, orthography is likely not the only factor leading to a left-to-right bias. When looking at early ontogeny, there may be other factors that play a role, such as the fact that when children count an array of objects, they habitually start on the left side (Briars and Siegler, 1984; Geary et al., 1992). Moreover, people in many Western societies conventionally start counting with their left hand (Lindemann et al., 2011). Finger counting direction has also been shown to modulate or even reverse the SNARC effect (Fischer, 2008; Pitt and Casasanto, 2014), suggesting that manual practices besides writing can influence the orientation of the mental number line.

Western adults are moreover constantly exposed to pictures, graphs and other representations that are structured in accordance with the left-to-right orientation of the mental number line (Maass and Russo, 2003; cf. Tversky, 2011). For example, in Western cafes and restaurants, prices are often listed in columns, with smaller prices on the left and larger prices on the right. Standard keyboard arrangements of numbers have the same orientation. Elementary school children may already know these biases and reproduce them in sorting tasks (Tversky et al., 1991). Evidence for the role of visual representations also comes from a study of Bächtold et al. (1998) where traditional left-to-right SNARC effects were observed when people were primed with a picture of a horizontally oriented ruler, but a reverse SNARC effect (right-to-left) was observed when participants were primed with a picture of a clock face (where overall smaller numbers are on the right side).

In line with the idea of "convergent cultural support," there also is a consistency between horizontal associations of quantity and horizontal associations of time (recently reviewed in Bonato et al., 2012; Bender and Beller, 2014). For example, calendars list days and months from left to right and corresponding to this, the associated numerals (day 1, 2, 3, etc.) are increasing. Behaviorally, it has been found that speakers of English gesture toward the left when talking about earlier events and to the right when talking about later events (Cooperrider and Núñez, 2009; Casasanto and Jasmin, 2012; Walker and Cooperrider, 2015). Moreover, visual primes affect temporal judgments consistent with a left-to-right going mapping (Núñez et al., 2006), and —similar to the horizontal SNARC—people also respond quicker with their left hand to past events and with their right hand to future events (Weger and Pratt, 2008; for a related effect, see Santiago et al., 2007).

From this perspective, writing direction is just one of several components of cultural support for horizontal spatial mappings of quantities and their symbols. Cognitive anthropologists have noted that external representations such as graphs and notation systems influence our mental representations (Bender et al., 2010; Zhang and Norman, 1995; Hutchins, 2010). That we are constantly surrounded by horizontal space-number mappings, and by consistent space-time mappings, suggests that these cultural reflections may have a causal role in shaping space/number mappings. This is indeed expected because of Hebbian learning (Hebb, 1949). If children are constantly exposed to practices (such as counting from left to right) and artifacts where space and number are correlated, this necessarily leads to neural and mental associations between co-occurring sensory-motor and conceptual activations.

3.3. *Sources of vertical mappings*

Similar to the horizontal mappings, there is a lot of convergent cultural support for vertical mappings of numbers onto space. However, when it comes to sources of vertical number-space associations, the picture is more complex. First, it is clear that writing direction does not explain the orientation of vertical SNARC effects: Whereas writing orientation along the horizontal axis corresponds to the horizontal SNARC effect (left-right), writing orientation along the vertical axis (top-down) would predict that smaller numbers should be associated with higher vertical space and larger numbers with lower vertical space (see Hubbard et al., 2005: pp. 437–438; cf. discussion in Ito and Hatta, 2004). In fact, this orientation has been found, but only with Chinese participants when responding to number words written in Chinese script, which is frequently written top-down in columns (Hung et al., 2008). Hence, if anything, writing orientation stands in opposition to the commonly observed vertical SNARC effect, and may in some cases, such as Chinese number words, override the small/low-large/high association.

Instead, Hubbard et al. (2005) point to the potential role of graphing conventions. Indeed, scientific graphs (e.g., bar plots: see Fischer et al., 2005) observe the principle of “more is up” (cf. Tversky, 2001, 2011). And so do other cultural devices, such as thermometers, measuring cups, body height measurement devices, and floor numbers in elevators. However, as has been frequently observed (e.g., Holmes and Lourenco, 2011), many cultural examples run counter to this orientation, for example, calendars, league tables, calculators and the number keys on cellphones. Most often, however, these apparent inconsistencies can be resolved by pointing out that numbers are not used in a cardinal sense in such situations. On calendars and league tables, the use of numbers (with “1” being at the top, rather than the bottom), is a purely ordinal one, i.e., “first place,” “second place” and so on. When using cellphones, we use numbers in a nominal sense, with one telephone number not being “more” or “less” than another telephone number, but simply identifying a specific identity. The cultural representations and artifacts where the mapping *is* consistent with an upward oriented number line, on the other hand, tend to emphasize quantities (e.g., measuring cups) where “more” and “less” are clearly defined.

In line with the idea of convergent cultural support, vertical mappings might also stem from another set of conventions, namely, linguistic expressions such as *high number* or *low number*, as discussed above (Section 2.2). The prevalence of talking about numbers and quantities in terms of vertical space supports vertical mental associations, but not horizontal ones (we do not talk about *right numbers* and *left numbers*, at least not in the same way we talk about *high numbers* and *low numbers*)[2].

However, even though vertical SNARC effects might stem from cultural or linguistic conventions, they probably have a deeper origin. It has often been pointed out that verticality and quantity are correlated in the natural world. Lakoff (1987: 276), for example, observes that “whenever we add *more* of a substance—say, water to a glass—the level goes *up*. When we add *more* objects to a pile, the level *rises*. Remove objects from the pile or water from the glass, and the level goes down.” Repeatedly observing and interacting with natural quantities that obey the principle of “more is up” is thought to mentally engrain the corresponding mapping (Lakoff, 1987; Lakoff and Johnson, 1980; Kövecses, 2002; cf., Fischer, 2011, 2012). Thus, it is conceivable that the natural correlation between verticality and quantity is the ultimate source of the mental association between vertical space and cardinal number, including all the linguistic and graphic reflections. From the perspective of child ontogeny and Hebbian learning, however, the natural correlation between verticality and quantity stands next to the graphic, gestural (Winter et al., 2014) and linguistic associations between verticality and quantity. Together, culture and the natural world make a set of stimuli available to the growing child where vertical space and quantity (or its symbolic expression) are associated in a highly predictable fashion.

3.4. *Sources of distance-based mappings*

Distance-based effects are sometimes discussed in relation to a generalized magnitude system in the brain that codes visual and spatial as well as temporal and motoric magnitudes (i.e., a theory of magnitude or ATOM: Walsh, 2003, 2015; Bueti and Walsh, 2009; Winter et al., 2015). The argument is that participants flexibly assign magnitudes to any spatial dimension that a task provides (see also, Holmes and Lourenco, 2011; Grade et al., 2013: 128). For distance-based effects, nearby space is a small spatial magnitude away, which maps onto small numbers. On the other hand, a large spatial magnitude (i.e., far space) maps onto large numbers. Hence, in line with ATOM, distance-based effects might be an indication of “more is more,” where “more” numerosity corresponds to “more” distance. The distance-based effects would then stem from the fact that both magnitudes access the same neural substrate (often postulated to lie within the intraparietal sulcus, see Walsh, 2003). However, as we pointed out above, the major share of evidence for distance-based effects stems from experiments that test specifically the sagittal axis, or the front/back dimension. While ATOM is compatible with sagittal mappings, it does not concretely explain why distance-based mappings should be oriented along this particular axis. Instead, ATOM would seem to predict distance-based effects that are radial.

In contrast to magnitude-based proposals, others allude to cultural support from space/time mappings (e.g., Seno et al., 2012; Marghetis and Youngstrom, 2014). For example, Marghetis and Youngstrom (2014) discuss connections between a sagittal number line and a sagittal time line, which maps the presence on the “ego,” soon-to-occur events onto near space, and future events onto far space. Speakers of English, for example, talk about looking *forward* to the future and thinking *back* to the past, and their gestures can reveal a sagittal orientation (Núñez et al., 2006). When participants are moved forward using a body-lifting device, they more quickly process future related words (Hartmann and Mast, 2012). They also

[2] Some linguistic metaphors may actually create novel conceptual mappings, such as the mapping of horizontal left/right space onto political positions (Oppenheimer and Trail, 2010), which has been argued to stem from expressions such as *right-wing conservative* and *liberal left* (Casasanto, 2013). In other cases, cognitive linguistic research has shown that the processing of linguistic metaphors involves active conceptualization of the metaphorical source domain such as space (Katz et al., 1998; Gibbs, 1994, 2006; Gibbs and Matlock, 2008). This type of research suggests that hearing about metaphorical vertical language in the context of number is likely going to reinforce those mappings.

respond more quickly with a response away from their body when reading about future events, and toward their body when reading about past events (Sell and Kaschak, 2011). These studies reveal a mental sagittal axis for the conceptualization of event sequences. Initial support for a link between time lines and number lines comes from a study (Matlock et al., 2011) showing that counting "upward" (5, 6, 7, . . .) or "downward" (17, 16, 15, . . .) leads to reliable shifts in temporal reasoning. However, ultimately, whether cognitive congruency between spatial mappings of time and number underlies the sagittal number-space mapping remains to be shown.

One alternative proposal for the origin of distance-based SNARC effects is that they might be derived from vertical effects (see also Holmes and Lourenco, 2011). This proposal has considerable support from neuroscience. Arguments have been made for a functional association between the lower visual field and proximal space and the upper visual field and distal space (Previc, 1990). When performing actions in peri-personal space, we often do so in the lower visual field. And when looking toward extra-personal space, we often do so in the upper visual field. People more quickly detect stimuli in the upper visual field when they appear distal (Levine and McAnany, 2005), and reports have been made about neural associations between vertical and distal space, for instance in a stroke patient with neglect of both up and far space (Shelton et al., 1990), and in another stroke patient with neglect of both low and near space (Mennemeier et al., 1992). Near and low space are also associated in our ecology and in linguistic metaphors, for example, we commonly understand a page oriented on a table in terms of "up" (far) and "down" (near) (Tversky, 2011: 506).

Again, we should notice that there is consistency between these different accounts for the origins of spatial–numerical mappings. ATOM associates far space with "more"; many time lines and gestures of time lines have the same association (with the future and associated larger numerical values being in the distance); and both vertical and distal space are cognitively and neuronally associated, as shown by the case of neglect. Hence, again, we are faced with multiple potential sources that are not mutually exclusive. Such a situation is to be expected if culture reflects brain organization, and if people (and children) automatically build up consistent neural and cognitive associations based on sets of correlated stimuli.

3.5. An alternative account: polarity correspondence

A specific proposal that can potentially account for spatial–numerical associations along all three dimensions is the so-called "polarity correspondence principle" (Proctor and Cho, 2006). This account is based on the observation that many dimensions have binary opposites, such as tall versus short. These oppositions are often asymmetrical. For example, we tend to ask a question about a person's height using *How tall is she?* but not *How short is she?* (cf. discussion in Roettger and Domahs, 2015). The pole of a dimension that can stand in for the entire dimension (in this case, *tall*) is called the "unmarked" case. In everyday language, this unmarked member of a binary pair is generally more frequent than the marked member (Roettger and Domahs, 2015; see also Hutchinson and Louwerse, 2014). Given these asymmetrical dimensions, the polarity correspondence principle states that if the polarity of the response dimension and the polarity of the stimulus dimension match, processing is facilitated. If the stimulus and response dimension mismatch, processing is slowed down. This can explain the SNARC effect if one assumes that the right side and large quantities are [+] polar, and the left side and small quantities are [−] polar (Proctor and Cho, 2006; Santens and Gevers, 2008). The right side is typically assumed to be [+] polar because right-handedness is the more frequent case in the population (see discussion in Roettger and Domahs, 2015), and given that the corresponding adjective *right* is more frequent than *left*.

The polarity correspondence account makes the right predictions for all three of the axes considered in this paper because *right, up* and *far* would all be considered as [+] polar (e.g., we would generally ask *How far is it*? rather than *How near is it?*, and the words are more frequent than their opposites *left*, *down* and *near*). Processing is predicted to be faster if these [+] polar poles of the respective dimensions match with [+] polar quantities (large numbers), and likewise if the [−] polar *left, down* and *near* responses match with the [−] polar small numbers. As such, the polarity correspondence principle is a unifying explanatory account for many of the effects considered in this paper so far. Critically, if polarity correspondence is correct about SNARC effects, these effects would not be because of spatial mental representations per se, but rather due to overlapping asymmetries of the corresponding numerical and spatial dimensions. That is, SNARC effects would arise because of structural similarity between response and stimulus rather than because of perceptual similarity.

However, there are several strands of evidence to suggest that the polarity correspondence principle cannot be the whole story for the SNARC effects considered in this paper. First, its primary explanatory domain contains tasks that involve binary stimulus and response dimensions. This is the case for many of the horizontal (e.g., Dehaene et al., 1993), vertical (e.g., Holmes and Lourenco, 2011) and distance-based mappings (e.g., the table-top response options in Ito and Hatta, 2004; Müller and Schwarz, 2007; Shaki and Fischer, 2012) considered in this paper, but it is not the case with the random number generation experiments discussed above, for which there is no binary response dimension (e.g., Loetscher et al., 2008b, 2010; Winter and Matlock, 2013). Another experiment that has no binary response dimension was conducted by Fischer and Shaki (2015), who found spatial numerical associations in a go/no-go task involving a single response.

Second, it is not clear whether polarity correspondence extends to the above-discussed associations between space and mental arithmetic (is addition [+] polar?). Third, novel experimental evidence indicates that both space-based and polarity correspondence-based accounts may coexist, but at different time scales: Roettger and Domahs (2015) find a SNARC effect for singular versus plural nouns (e.g., *house* versus *houses*) with singulars being faster with left responses and plurals being faster with right responses. This result is consistent with a spatial representation of quantity but inconsistent with polarity correspondence, which regards singulars as [+] polar and plurals as [−] polar. The SNARC effect in Roettger and Domahs (2015), however, was observed only for late response times. For early response times, results were consistent with the polarity correspondence principle (faster *left* responses to plurals).

The polarity correspondence principle furthermore makes inconsistent predictions with respect to word frequency: Linguists generally assume that the unmarked member of a pair (e.g., *tall*) is also more frequent in spoken language and texts (for discussion see Hutchinson and Louwerse, 2014). However, large numerals, which are assumed to be [+] polar (Proctor and Cho, 2006), are more frequent than small numerals, which are [−] polar. Finally, it is not clear that the polarity correspondence principle applies to effects that relate to space/time mappings, which, given their directional consistency with SNARC effects, seem to be tapping into some of the same cognitive processes.

So, the polarity correspondence principle may be a powerful explanation of SNARC effects in some of the binary tasks considered above, but it does not account for all patterns observed and makes some inconsistent predictions. Moreover, what exactly counts as [+] polar and [−] polar is not always straightforward (see discussion in Roettger and Domahs, 2015). The above-discussed embodied

Table 1
Comparison of strength of horizontal, vertical and sagittal effects for those studies that had multiple response dimensions in the same task.

	Task	Results		
Truly vertical				
Schwarz and Keus (2004)	Eye	H*	>	V*
Loetscher et al. (2008)	Eye	H*	>	V
Loetscher et al. (2010)	RNG	H*	<	V*
Grade et al. (2013)	RNG	H*	>	V*
Hartmann et al. (2012)	RNG	H*	>	V*
Winter and Matlock (2013)	RNG	H*	<	V*
Wiemers et al. (2014)	Arithmetic	H	<	V*
Sell and Kaschak (2012)	Linguistic	H	<	V*
Sagittal				
Gevers et al. (2006)[a]	SNARC	H*	>	S
Ito and Hatta (2004)[b]	SNARC	H*	<	S*
Müller and Schwarz (2007)[c]	SNARC	H	<	S*

">" and "<" indicates which effect is *numerically larger*, the star indicates whether the corresponding effect was found to be significant.
[a] Results from Experiment 1 (Experiment 2 is diagonal).
[b] Results not strictly speaking comparable due to dependence on hand assignments.
[c] Results from Experiment 1.

accounts of three-dimensional SNARC effects are equally plausible and have the advantage of fitting firmly into the body of existing linguistic and anthropological research.

4. Relationships between SNARC effects

Are the three spatial–numerical associations (horizontal, vertical, radial) equally well entrenched? Or is one axis more cognitively dominant than the others? Currently, there is disagreement about whether the horizontal or the vertical SNARC effect is stronger, with some researchers asserting that vertical space may be the "predominant dimension in the organization of number space" (Wiemers et al., 2014: 12), and others saying that "the vertical mode of representation is not the preferable one" (Gertner et al., 2013: 1354). Yet, very few studies explicitly compared these two effects, and many have not taken into account the differences between sagittal and truly vertical SNARC effects. Table 1 provides a list of those studies that have tested at least two axes for the same participants.

Table 1 suggests equivocal evidence with respect to the strength of vertical and horizontal SNARC. Some studies show that horizontal and vertical SNARC effects are of similar strengths, as with random number generation studies (Loetscher et al., 2010; Grade et al., 2013) and an eye tracking study (Schwarz and Keus, 2004). On the other hand, some studies indicate that vertical effects are stronger (e.g., Wiemers et al., 2014; Winter and Matlock, 2013; Sell and Kaschak, 2012).

4.1. Pitting horizontal and vertical SNARC effects against each other

A few studies have directly pitted horizontal and vertical SNARC effects against each other by using diagonal response mappings (Holmes and Lourenco, 2011, 2012; Gevers et al., 2006). The logic behind these studies is that in a congruent condition, responses are delivered along the "right-diagonal," precisely, from a lower left response location for small numbers to an upper right response location for large numbers. Thus, there is a congruency between the horizontal and the vertical mapping that results from an association of small numbers with the lower and the left side. In an incongruent condition, responses are delivered along the "left-diagonal," precisely, from an upper left response location to a lower right location. So, in this incongruent condition, there is a conflict between the horizontal and vertical mapping preferences. A response to a smaller number on the left side is compatible with the horizontal number line but simultaneously incompatible with the vertical one, and likewise for lower right responses to large numbers.

Gevers and colleagues (2006) used keypad responses, a setup that is not truly vertical but relates to the sagittal effects discussed above. They observed neither a horizontal nor a vertical effect in an incongruent diagonal condition (e.g., left-top/right-bottom). In a similar setup, Holmes and Lourenco (2011, Experiment 1B) observed a sagittal but no horizontal effect. A similar task with a diagonal response setup on a vertically mounted touch screen found that the horizontal effect "trumps" the vertical one (Holmes and Lourenco, 2012); i.e., there was a horizontal effect, but no vertical effect in the left-diagonal incongruent condition.

To interpret the relevance of these findings, it is important to ask whether SNARC effects are truly defined along the diagonal axis. Several findings suggest that associations between numbers and space are primarily oriented along distinct cardinal axes (horizontal, vertical, sagittal), rather than being map-like (as suggested by e.g., Schwarz and Keus, 2004). Remember that broadly construed, numerical cognition is consistent with other domains of brain organization, cognition and culture (Section 3). Here, we would like to point out that visual discrimination is best along the vertical and horizontal axis, not a diagonal axis (the so-called "oblique effect," see Appelle, 1972; Lechelt et al., 1976; cf. Howard, 1982). Franklin and Tversky (1990) argue that when people search imagined environments, they preferentially access objects along specific axes, rejecting the hypothesis that all directions extending from the body are equally available. Moreover, numbers are generally not presented diagonally or grid-like in our culture, but instead, aligned *either* horizontally *or* vertically (e.g., bar plots, menu price lists, etc.) (cf. discussion in Tversky, 2011). Children, for example, learn numbers on the number line before they learn the Cartesian coordinate system. In line with this evidence, when blindfolded participants position numbers in three-dimensional space (Fischer and Campens, 2009), they spontaneously exploit horizontal, vertical or radial dimensions—but critically no diagonal orientations.

We can therefore question the legitimacy of generalizing from diagonal orientations (as in Holmes and Lourenco, 2012 and Gevers et al., 2006) to other experiments that report purely vertical and horizontal mappings. Along the same lines, we can question the legitimacy of generalizing from the presence of purely horizontal and vertical effects (as in Schwarz and Keus, 2004) to diagonal or grid-like mappings. The evidence from perceptual organization and cultural representations suggests that diagonal representations of numbers are unnatural or unrelated to the other documented SNARC effects.

More generally, when pitting the horizontal and vertical axis against each other, other types of perceptual and spatial asymmetries may be confounded with differences in the strength of the spatial–numerical associations. Horizontal and vertical space are asymmetrical in perception and action—regardless of any associations to numbers. For example, it has been suggested that the visual search field is of greater horizontal than vertical extent (Chaiken et al., 1962; Ikeda and Takeuchi, 1975; Previc and Blume, 1993), as depicted in Fig. 2. Children also scan more widely and frequently along the horizontal than the vertical axis (Haith, 1980). Moreover, adults tend to perform smaller vertical head movements than horizontal ones (Glenn and Vilis, 1992; Pelz et al., 2001) and vertical lines are perceived to be longer than horizontal lines of equal length (Finger and Spelt, 1947; Higashiyama, 1992). There are also asymmetries of horizontal and vertical space in our environment. For example, rooms are generally more horizontally than vertically extended, and most people more frequently move horizontally than vertically.

For the experiments reporting explicit comparisons between the horizontal and the vertical axis, such asymmetries could matter.

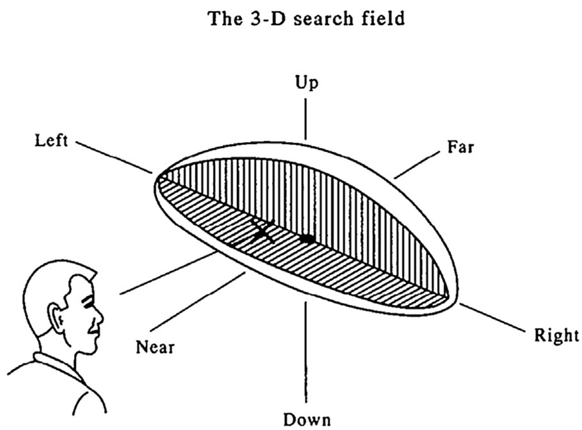

Fig. 2. Visual search field sketched by [108, p. 2703] with fixation at *X* and center of the ellipsoid at the black dot. The visual search field is less extended along the vertical axis than along the horizontal axis.

Source: Reprinted from Previc and Blume (1993), with permission from *Elsevier*.

For example, the screen on which the numbers were displayed in Holmes and Lourenco (2012, see Fig. 1, p. 1046) had more horizontal than vertical extent. This saliency of the horizontal perceptual dimension could have biased participants in favor of horizontal number-space mappings. Similarly, because of horizontal–vertical asymmetries for movements—including eye movements (Collewijn et al., 1988)—we cannot take for granted that a diagonally oriented response orientation with equal physical extent in the horizontal and vertical dimension is, in fact, perceived as equal. So, if we find one effect to be stronger in a particular task, is it the result of representational space or the differential perception of the task dimensions? In general, it is difficult to draw hard and fast conclusions about relative strength from horizontal versus vertical comparisons if the horizontal and vertical dimensions are not equally scaled psychophysically.

Moreover, our discussion in Section 3 leads us to ask why should one effect be stronger than the other across the board? Given the multifarious cultural and non-cultural phenomena that may lead to space/number mappings, we may not want to make claims about one effect being stronger than the other *in all contexts*. Instead, experimental effects of spatial–numerical associations might be stronger for some axes in some tasks, and for other axes in other tasks. In the next section, we relate the multi-causal origins (Section 3) of space/number mappings to specific task-dependent predictions.

4.2. Relating origins to predictions

Given that spatial–numerical associations may arise from a wealth of different cultural and embodied phenomena (see Section 3), we expect to see task-dependent differences on a priori grounds. As discussed, besides its cultural reflections, the vertical space/number association is thought to be grounded in natural correlations (Fischer, 2011, 2012; Fischer and Brugger, 2011; cf. Lakoff, 1987; Lakoff and Johnson, 1980). Given this, we might expect that in concrete physical situations (i.e., reasoning about quantities of objects or amounts of liquids), vertical effects would be stronger than horizontal effects. Initial evidence already supports this prediction. As described above, Pecher and Boot (2011) found vertical attentional SNARC effects with sentences that imply concrete quantities, such as *The man had two books in his bookcase*—but not with numerals outside of any physical contexts. In another experiment (Holmes and Lourenco, 2012), the vertical SNARC effect re-emerged only when participants were primed to think about building floors (first floor, second floor, etc.). More studies implementing concrete horizontal and vertical scenarios to contextualize number meanings are needed.

Another prediction that can be derived from the above discussion is that the vertical SNARC effect—because of its connection to language (e.g., *high number*, *low number*, etc.)—should be stronger in linguistic contexts, at least compared to horizontal effects that have no such linguistic support. Initial evidence (Sell and Kaschak, 2012) suggests that this may indeed be the case. SNARC effects with truly vertically aligned response buttons were found in response to linguistic stimuli such as *More/less runs were being scored in this game*, but no horizontal effects emerged in this situation. Likewise, many studies that did find vertical effects were random number generation tasks (Hartmann et al., 2012; Loetscher et al., 2010; Grade et al., 2013; Winter and Matlock, 2013), which, by virtue of asking participants to verbalize, necessarily have a linguistic component. Finally, as discussed above, numerical magnitude interacts with the vertical location implied by words such as *foot* and *bird* (Lachmair et al., 2014). However, a direct comparison of horizontal and vertical effects in both linguistic and non-linguistic contexts is still outstanding.

The diverse set of potential cognitive origins furthermore leads us to expect the different axes to be at least partially dissociated across spatial–numerical tasks. At present, the evidence for this is not straightforward. Gevers and colleagues (Gevers et al., 2006) found a strong correlation between horizontal and sagittal SNARC effects ($r = 0.75$) while others (Bogdanova et al., 2008) found a somewhat weaker correlation for horizontal and vertical number line bisection ($r = 0.52$ and $r = 0.47$). Finally, others found that head movements along the horizontal and head movements along the vertical axes where largely unrelated when it came to random number generation (Winter and Matlock, 2013); participants in this study predominantly *either* had a horizontal *or* a vertical mapping. Horizontal and vertical orientations of number lines can furthermore be dissociated in neglect (Cappelletti et al., 2007), and they interact differently with the size congruency effect and the numerical distance effect (Gertner et al., 2013; Cohen Kadosh et al., 2007; Gertner et al., 2009), suggesting neural dissociation.

Unfortunately, at present many studies exploring both horizontal and vertical/sagittal space for the same subjects fail to report whether these effects are correlated, hence limiting our conclusions at this point. Future research needs to explore more systematically how horizontal, vertical and sagittal effects are correlated across different individuals and different tasks. Are some people more inclined to think about numbers vertically, and others more inclined to think about numbers horizontally or radially? That the answer may turn out to be "yes" is suggested by a free placement task (Fischer and Campens, 2009), where different participants spontaneously mapped numbers onto different spatial axes with idiosyncratic, participant-specific choices. Finally, given the fact that near/far space frequently correspond to each other in perception (see Section 3.4), we might expect that sagittal SNARC effects should be most strongly correlated with vertical SNARC effects across individuals, more so than with horizontal SNARC effects.

The view that vertical SNARC effects stem from the physical and cultural world, whereas horizontal SNARC effects largely stem from cultural conventions also makes the prediction that vertical SNARC effects should be found in any culture, compared to horizontal SNARC effects, which are known to be culturally relative (Dehaene et al., 1993; Zebian, 2005; Göbel et al., 2011), with different orientations for different cultures.

5. Conclusions

More and more studies on numerical cognition are beginning to find associations between numerical magnitude and space, not just along the horizontal axis but also along the vertical and sagittal ones. Here, we have synthesized the evidence for these other, non-horizontal mappings between space and number. We have highlighted that the evidence points toward the co-existence of multiple spatial mappings (cf. Shaki and Fischer, 2012; Winter et al., 2014, 2015). The evidence for vertical and sagittal SNARC effects is strong. And despite common belief to the contrary, as discussed above, these more recently discovered effects are sometimes equally strong or stronger than the more established horizontal SNARC effect.

However, we have also pointed out that the relative strength of associations depends to a large extent on the tasks considered. Whereas the set of tasks that have explored horizontal effects is vast—including all kinds of response setups and representation formats—the range of tasks used for vertical and sagittal effects is currently somewhat limited. Only with more studies on non-horizontal SNARC effects can we begin to address the questions raised in this paper. We have reviewed the potential sources of horizontal, vertical and sagittal SNARC effects, which lead us to make testable predictions for specific tasks environments in future experiments.

Overall, our review fits a view of numerical cognition that holds that knowledge representation is rich and flexible. Besides number lines on the three axes reviewed here, other research points to associations between numbers and size (Henik and Tzelgov, 1982), abaci (Frank and Barner, 2011) and fingers (Di Luca et al., 2006; Fuson, 1988; Noël, 2005; Fischer, 2008; Wasner et al., 2014; Fischer and Brugger, 2011). All of these can be argued to stem from experience. Thus, the picture we are left with does not feature one dominant spatial representation but rather a multitude of flexible ways of thinking about numbers that arise through experience. Rather than viewing multiple spatial mappings as competing with each other and asking questions about which is the preferred mapping, we might view this multitude as part and parcel of numerical cognition and mathematical practice (cf. Marghetis and Núnez, 2013; Lakoff and Núñez, 2000, Ch. 3; Winter et al., 2014). Having multiple ways of thinking about numbers might help us deal with situated and specific contexts in which we use these numbers. It also helps us approach the same problem from multiple directions. Most importantly, the presence of multiple spatial mappings reminds us that number knowledge is, like all other knowledge, a reflection of our experience in a three-dimensional world.

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