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Review

Of magnitudes and metaphors: Explaining cognitive interactions between space, time, and number

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ABSTRACT

Space, time, and number are fundamental to how we act within and reason about the world. These three experiential domains are systematically intertwined in behavior, language, and the brain. Two main theories have attempted to account for cross-domain interactions. A Theory of Magnitude (ATOM) posits a domain-general magnitude system. Conceptual Metaphor Theory (CMT) maintains that cross-domain interactions are manifestations of asymmetric mappings that use representations of space to structure the domains of number and time. These theories are often viewed as competing accounts. We propose instead that ATOM and CMT are complementary, each illuminating different aspects of cross-domain interactions. We argue that simple representations of magnitude cannot, on their own, account for the rich, complex interactions between space, time and number described by CMT. On the other hand, ATOM is better at accounting for low-level and language-independent associations that arise early in ontogeny. We conclude by discussing how magnitudes and metaphors are both needed to understand our neural and cognitive web of space, time and number.

1. Introduction

Our everyday interactions with the world depend on being able to perceive and understand space, time, and number, and these three domains are tightly entwined throughout human experience and behavior. A large and growing literature has documented cross-domain interactions between space, time, and number—from low-level perception to high-level linguistic systems, in both brain and behavior. Two prominent theories have tried to account for these interactions. Walsh (2003) posits a domain-general representation of magnitude, and argued that behavioral cross-domain interactions emerge from a shared reliance on the same neural resources. This proposal is called *A Theory of Magnitude* (ATOM). On the other hand, *Conceptual Metaphor Theory* (CMT) posits that we understand abstract domains by mapping them onto our understanding of more concrete domains, such as physical space (Gibbs, 1994; Kövecses, 2002; Lakoff, 1993, 2008; Lakoff & Johnson, 1980, 1999).

Both theories share a common explanatory target: interactions between space, time, and number. They address

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these interactions, however, at different timescales and levels of analysis, focusing on different sources of evidence, and often relying on different methods. Many studies in support of ATOM involve neuroimaging and relatively low-level psychological tasks, typically emphasizing psychophysics and automatic perceptual processing. The evidence for CMT, by contrast, typically comes from behavioral studies of reasoning and language comprehension, or descriptive analyses of language and gesture. Perhaps because of these different approaches, or perhaps because of their different disciplinary origins, the two theories are infrequently juxtaposed and compared (for exceptions, see Anderson, 2010; Bottini & Casasanto, 2010a, 2010b, 2013; Casasanto, Fotakopoulou, & Boroditsky, 2010; Merritt, Casasanto, & Brannon, 2010; Srinivasan & Carey, 2010). When they *are* juxtaposed, they are often treated as competing accounts that make incompatible predictions (Bottini & Casasanto, 2010a, 2010b, 2013; Merritt et al., 2010). And yet there are striking similarities in the cross-domain interactions found in language, reasoning, psychophysics, and brain activity—similarities that invite an integrated explanation.

In this paper, we survey ATOM, CMT, and the evidence put forth in support of each theory. The first goal is to introduce the two theories and their accompanying evidence to a general audience (§2). The second is to evaluate obstacles to the theoretical integration of ATOM and CMT. The two theories have been contrasted on the degree to which they predict "asymmetries" in cross-domain interactions—that is, whether one domain influences another domain more so than vice versa. We offer conceptual clarification of this notion, in order to ground the discussion of behavioral and neural cross-domain asymmetries (§3). The two theories also differ in terms of scope and level of specificity; ATOM focuses on interactions between low-level magnitudes while CMT focuses on the role of high-level reasoning and language understanding (§4). Finally, we discuss the theories' shared commitment to the functional relevance of these cross-domain interactions, and survey the evidence that associations between space, time and number play a functional role in perception, reasoning, and language (§5). Overall, our review supports a pluralistic approach that understands ATOM and CMT as mutually compatible.

2. Explaining space, time, and number in the brain

2.1. ATOM

Walsh (2003) proposed that the seemingly distinct domains of space, time and number are processed by a single cross-domain magnitude system in the brain, a proposal that he dubbed *ATOM*. This domain-general magnitude system is thought to be involved in processing spatial, numerical and temporal magnitudes—including length, area, volume, numerosity and temporal duration—as well as other perceptual magnitudes such as luminance and loudness. ATOM addresses domains that we experience in terms of "more than" or "less than"—so-called "prothetic" perceptual dimensions—which can be laid out along a continuous scale of increasing or decreasing magnitude (cf. Stevens, 1975).

ATOM argues that this shared neural substrate confers adaptive benefits because it supports the coordination of magnitudes relevant to action (Bueti & Walsh, 2009; Walsh, 2003). For example, when human and non-human animals grasp a pile of nuts, magnitude is relevant to perceiving how many nuts there are and how distant the pile is. These numerical and spatial magnitudes, in turn, determine grip aperture and reach distance. In general, all kinds of actions, including grasping, throwing, pointing, and running, require simultaneously coordinating multiple spatial, temporal, and numerical magnitudes. According to ATOM, furthermore, the human ability to count and calculate—which involve operations that can be characterized in terms of "more than" and "less than"—also depends on the evolutionarily-ancient magnitude system (Bueti & Walsh, 2009).

The neural substrate of the proposed cross-domain system is thought to lie primarily within regions of parietal cortex. Neuroimaging studies find that the bilateral intra-parietal sulcus (IPS) and surrounding areas are activated when processing either spatial or numerical magnitudes (Hubbard, Piazza, Pinel, & Dehaene, 2005; Kaufmann et al., 2008; Pinel, Piazza, Le Bihan, & Dehaene, 2004). The IPS is also implicated in temporal perception; for example, there is an increased BOLD signal in the left IPS when a task requires attention to temporal intervals (Coull & Nobre, 1998). Moreover, using transcranial magnetic stimulation (TMS) to induce targeted disruptions of posterior parietal cortex causes selective deficits in the processing of spatial, temporal and numerical magnitudes (reviewed in Sandrini & Rusconi, 2009). For example, TMS to the right IPS interferes with spatial and numerical magnitude processing (Cohen Kadosh, Cohen Kadosh, Schuhmann, et al., 2007; cf. Andres, Seron, & Olivier, 2005). This functional specialization appears to be shared with non-human primates: Regions of macaque parietal cortex, homologous to human IPS, are active when processing spatial extent (Stein, 1989), temporal duration (Leon & Shadlen, 2003; Onoe et al., 2001), and numerical magnitude (Sawamura, Shima, & Tanji, 2002). Some of the most conclusive evidence for a common magnitude processing comes from single-cell recording studies of monkeys, which have found neurons within the IPS that are tuned both to spatial and to numerical magnitudes (Tudusciuc & Nieder, 2007). It should be noted, however, that even though ATOM predicts that space, time, and number should share cortical circuitry, it does not claim that this circuitry must be restricted to a single, localized region. The magnitude system, even though it is concentrated in the parietal cortex, presumably involves a distributed but integrated system of brain regions, including prefrontal cortex (cf. Bueti & Walsh, 2009: 1836).

The clinical literature presents further evidence of a shared representation of space, time, and number. Lesions to the parietal cortex often result in hemispatial neglect, in which visuospatial attention is disrupted to the space ipsilateral to the lesion. Critically, patients with left hemispatial neglect often exhibit selective "neglect" of other magnitude-related representations, including lesser (rather than greater) numbers (Zorzi, Priftis, & Umiltà, 2002) and events that happened earlier (rather than later) in time (Saj, Fuhrman, Vuilleumier, & Boroditsky, 2014). The typical size of lesions, however, limits us to drawing inferences about rather distributed regions of parietal cortex. Many other neurological disorders are associated with deficits in both spatial and numerical behaviors, including, Gerstmann's syndrome (Benton, 1992; Gerstmann, 1940; Kinsbourne & Warrington, 1962) and dyscalculia (Butterworth, Varma, & Laurillard, 2011; Rotzer et al., 2009). Asymptomatic HIV infection (Bogdanova, Neargarder, & Cronin-Golomb, 2008) affects both spatial and numerical abilities, and it is associated with tissue loss in (among other areas) the parietal cortex of HIV+ patients (cf. Bogdanova et al., 2008). Children with deletion of chromosome 22q11.2 have, among other things, abnormal parietal structures (Simon, Ding, Bish, McDonald-McGinn, Zackai, & Gee, 2005) and an associated co-morbidity of visuospatial and numerical abilities (Simon, Bearden, Mc-Ginn, & Zackai, 2005). In sum, converging evidence from imaging and clinical studies suggest that numerical, spatial, and temporal magnitudes rely on shared neural machinery that rests within parietal cortex.

ATOM makes a couple of key behavioral predictions. First, it predicts behavioral interactions between space, time and number, such that people should associate “more” in one domain with “more” in another (“more A-more B,” Bueti & Walsh, 2009). Second, it predicts that space, time and number should influence action (Bueti & Walsh, 2009). With respect to the first prediction, the fact that all of the three dimensions are governed by the Weber–Fechner law has been taken to suggest a shared representational system governed by the same psychophysical laws (Cantlon, Platt, & Brannon, 2009; Emmerton & Renner, 2006; Jordan & Brannon, 2006a, 2006b). In addition to this structural similarity, there is a wealth of studies reporting cross-domain behavioral interactions: Early work on cross-modal matching showed that people can reliably associate increases in the magnitude of one dimension with increases in the magnitude of another (Marks, 1974, 1989; Stevens, 1975; Stevens & Guirao, 1963; Stevens & Marks, 1965). Reliable cross-modal matching has also been shown for children of various ages (Lewkowicz & Turkewitz, 1980; Teghtsoonian, 1980). Thus, when asked explicitly, people can match different dimensions, and they do so consistently. Less explicit manipulations have also demonstrated automatic and systematic associations between different magnitudes: Xuan, Zhang, He, and Chen (2007) found an increase in perceived stimulus duration when the stimulus was increased in size, luminance or quantity. Srinivasan and Carey (2010) showed that infants are more likely to remember pairings of lines and tones where length and duration are positively correlated than pairings where length and duration are negatively correlated (see also Lourenco & Longo, 2010).

One well-documented behavioral interaction between space and number is the *Size-Congruency Effect*: When responding to a visually displayed numeral, participants respond slower if the font size is incongruent with the represented numerical quantity (e.g., a small number in large font), but faster if they are congruent (e.g., a small number in small font) (Cohen Kadosh, Cohen Kadosh, Linden, et al., 2007; Cohen Kadosh, Cohen Kadosh, Schuhmann, et al., 2007; Henik & Tzelgov, 1982; Pinel et al., 2004). This suggests that a numeral's spatial extent interacts automatically with the numerical magnitude of the number it represents, as if participants confounded the two magnitudes.

In addition to interacting with spatial *extent*, both number (Dehaene, Bossini, & Gireaux, 1993; Wood, Nuerk, Willmes, & Fischer, 2008) and time (Ishihara, Keller, Rossetti, & Prinz, 2008; Santiago, Lupáñez, Pérez, & Funes, 2007; Torralbo, Santiago, & Lupiáñez, 2006) have been found to interact with spatial *locations*. The most well-known interaction between location and number is the Spatial Numerical Association of Response Codes, or SNARC effect (Dehaene, Bossini, & Giraux, 1993). Here, Western literate adults associate left responses with small magnitudes and right responses with large magnitudes. This effect is reversed in cultures that read both numbers and words from right to left (Shaki, Fischer, & Petrusic, 2009; cf. Zebian, 2005). The temporal equivalent of this numerical effect is the Spatial Temporal Association of Response Codes, or STEARC effect (Ishihara et al., 2008), in which horizontal locations are associated with the concepts of before versus after, or future versus past (Ishihara et al., 2008; Santiago et al., 2007; Torralbo et al., 2006; Vallesi, Weisblatt, Semenza, & Shaki, 2014; Weger & Pratt, 2008). In a related effect, participants perceive a stimulus presented on the left side to be shorter than a stimulus on the right side (Vicario, Pecoraro, Turriziani, Koch, & Caltagirone, 2008). The many similarities between the SNARC and STEARC effects suggest an integrated explanation (see Bonato, Zorzi, & Umiltà, 2012 for review). Walsh (2003) interpreted the SNARC effect as supporting ATOM, arguing that it should be understood as one instance of a more generalized Spatial Quantity Association of Response Codes (SQUARC) effect. Building on this, Bueti and Walsh (2009) argued that the temporal results of Ishihara et al. (2008) are another instance of such a SQUARC effect. SNARC- and STEARC-like effects have been found for locations along horizontal, vertical, near/far, and sagittal axes (Hartmann, Grabherr, & Last, 2011; Ito & Hatta, 2004; Loetscher, Bockisch, Nicholls, & Brugger, 2010; Marghetis & Youngstrom, 2014; Schwarz & Keus, 2004; Seno et al., 2012; Shaki & Fischer, 2012; Torralbo et al., 2006), effects which an ATOM theorist is likely to interpret as evidence of a general association between spatial locations, number, and time. These effects undeniably speak to the presence of some kind of association between space, number, and time (consistent with ATOM), but they involve interactions with spatial *location*, not spatial magnitude, and are, thus, not directly predicted by ATOM, a point to which we return below (§4).

ATOM's second key prediction is that the domain-general magnitude system affects actions, which has been confirmed across a variety of behavioral paradigms. For example, perceived numerical magnitude affects the grip size of subsequent reaching movements (Lindemann, Abolafia, Girardi, & Bekkering, 2007). Conversely, the graspability of a visually presented object influences subsequent numerical processing (Ranzini et al., 2011), and viewing “pinching” gestures interferes with the processing of larger magnitudes (Badets & Pesenti, 2010). Processing temporal concepts also influences actions, such as hand movements while operating a computer mouse (Miles, Betka, Pendry, & Macrae, 2010). Indeed, both the SNARC and STEARC effects are instances of effects on subsequent action, with representation-compatible actions (e.g., left response after small number) favored over non-compatible ones (e.g., right response after small number). Lastly, reaching-related behaviors depend on regions of human parietal cortex (Culham & Valyear, 2006) and purported homologous areas in monkeys (Sakata, Taira, Murata, & Seiichiro, 1995), consistent with the idea that the domain-general magnitude system located primarily within parietal cortex plays a functional role in guiding actions.

If, as ATOM argues, the cross-domain magnitude system evolved to support action (Bueti & Walsh, 2009; Walsh, 2003), then at least some aspects of this magnitude system should be innate and shared across species. This latter prediction is born out by the evidence, reviewed above, of a domain-general magnitude system in non-human primates (Leon & Shadlen, 2003; Onoe et al., 2001; Sakata et al., 1995; Sawamura et al., 2002; Stein, 1989; Tudusciuc & Nieder, 2007). Moreover, the Weber–Fechner law also characterizes within-domain judgments by infants and young children, suggesting that important properties of the magnitude system arise early in ontogeny (Feigenson, 2007; Lewkowicz & Turkewitz, 1980; Teghtsoonian, 1980). Cross-domain interactions between prothetic dimensions also appear early in development. Lourenco and Longo (2010), for instance, showed that 9-month-old infants associate large size with long durations. Even neonates as young as a few hours old seem to associate spatial extent, temporal duration, and approximate numerical magnitude (de Hevia, Izard, Coubart, Spelke, & Streri, 2014). There is evidence, therefore, that humans share an innate, domain-general magnitude system with other species, the product of shared evolutionary pressures or common descent (Bueti & Walsh, 2009; Walsh, 2003).

2.2. CMT

CMT takes as its starting point an observation about linguistic behavior: Talk of both time and number often recycles the language of space, and it does so in highly systematic ways (Lakoff, 1987; Lakoff & Johnson, 1980, 1999). For example, even though abstract number lacks literal height and changes in numerical magnitude do not involve literal motion, English speakers describe numbers as *high* or *low*, and changes in numerical quantities (e.g., prices, taxes, interest rates) as *rising* or *falling* (Lakoff, 1987: 276; Lakoff & Johnson, 1980: 15–16). English and other languages also recycle the language of physical size to describe numbers as *large* or *small* (Lakoff & Johnson, 1980). The same goes for time. In English, for example, we can say such things as: *I've been waiting a long time*, *Friday is ahead of us*, *Christmas has passed* or *The deadline is approaching*. In each case, we describe temporal events in terms of motion and spatial landmarks. Similar linguistic metaphors are ubiquitous not only in English but across the world's languages. Space-time metaphors have received the most attention by linguists, who have observed that nearly every attested culture uses some form of spatial metaphor to describe time (Alverson, 1994; Boroditsky & Gaby, 2010; Clark, 1973; Evans, 2004; Haspelmath, 1997; Lakoff & Johnson, 1999; Traugott, 1978; for a possible exception, see Sinha, Silva Sinha, Zinken, & Sampaio, 2011).

A central claim of CMT is that these systematic *linguistic* metaphors are not mere stylistic devices, but instead reflect entrenched *conceptual* mappings across cognitive domains (Lakoff & Johnson, 1980, 1999; Lakoff & Turner, 1989). According to CMT, we understand and talk about the so-called "target" domains of number and time by mapping them to the "source" domain of space. Though early evidence for CMT was almost entirely linguistic (Murphy, 1997), the last three decades has seen a growing body of non-linguistic evidence that conceptual metaphors guide reasoning, structure concepts, and even shape perceptual judgments, primarily using behavioral methods (for review, see Gibbs, 1994, 2006). According to CMT, for instance, numbers and arithmetic rely on a system of complementary spatial metaphors such as NUMBERS ARE COLLECTIONS, NUMBERS ARE LOCATIONS ON A PATH, and ARITHMETIC IS MOTION ALONG A PATH (Lakoff & Núñez, 2000), and there is mounting behavioral evidence that these metaphors structure mathematical reasoning, from early learning to advanced mathematical practice (for review, see Núñez & Marghetis, in press). In sum, CMT argues that numerical and temporal cognition build on a spatial foundation.

In English, time can be described from an "ego-moving" perspective (e.g., ***We*** *are quickly approaching the deadline*) or from a "time-moving" perspective (e.g., ***The deadline*** *is quickly approaching*). According to CMT, these alternative descriptions reflect alternative conceptual metaphors, and because they attribute motion to different entities—either "ego" or "time"—these complementary conceptual metaphors generate different responses to the following ambiguous question: "Next Wednesday's meeting has been moved forward two days. What day is the meeting now that it has been rescheduled?" (Boroditsky, 2000; McGlone & Harding, 1998). Boroditsky and Ramscar (2002) primed "ego-moving" and "time-moving" perspectives by asking participants to imagine self-motion or pulling a chair, respectively. As predicted by CMT, participants in the "ego-moving" condition were more likely to respond Friday, but participants in the "time-moving" condition were more likely to respond Monday, as if they were using space to reason metaphorically about time (see also Matlock, 2010; Matlock, Holmes, Srinivasan, & Ramscar, 2011; Matlock, Ramscar, & Boroditsky, 2005).

Moreover, there is a close correspondence between the conceptual metaphors proposed by CMT and the number-space and time–space interactions documented by cognitive psychology. For example, the above-mentioned STEARC effect—in which past and future are associated with left and right, respectively—is compatible with a conceptual metaphor in which times are conceptualized as spatial locations (Lakoff & Johnson, 1999). Similarly, the horizontal SNARC effect has been taken as evidence that numbers are represented as a mental number-line (Dehaene et al., 1993), which is compatible with the claim in CMT that numbers are conceptualized metaphorically as locations along a path (Lakoff & Núñez, 2000). Futhermore, Lakoff and Núñez (2000) proposed that we conceptualize arithmetic using the metaphor ARITHMETIC IS MOTION ALONG A PATH, and it has been found recently that addition and subtraction are associated with systematic rightward and leftward biases, respectively (Knops et al., 2009; Marghetis, Núñez, & Bergen, 2014; Pinhas & Fischer, 2008; Pinhas, Shaki, & Fischer, 2014), a finding that is compatible with the proposed metaphor (Núñez & Marghetis, in press). Finally, CMT claims that we conceptualize quantities using the metaphor MORE IS UP (e.g., "five is *higher* than four") (Lakoff, 1987; Lakoff & Johnson, 1980), which successfully predicts associations between vertical locations and numerical magnitudes (i.e., the vertical SNARC effect; Holmes & Lourenco, 2012; Müller & Schwarz, 2007; Pecher & Boot, 2011; Sell & Kaschak, 2012).

Support for the metaphorical understanding of number and time also comes from spontaneous co-speech gestures. Gesture often reflects spatial metaphors used to understand time, arithmetic, and number (Casasanto & Jasmin, 2012; Cooperrider & Núñez, 2009; Marghetis & Núñez, 2013; Núñez, 2009; Núñez & Marghetis, in press; Núñez & Sweetser, 2006; Winter, Perlman, & Matlock, 2014). Gesture sometimes reflects conceptual metaphors that are absent from speech, as when native speakers of English gesture leftward to indicate earlier events, and rightward to indicate later events (Casasanto & Jasmin, 2012; Cooperrider & Núñez, 2009). Similarly, when people reason about arithmetic, they often produce gestures that represent numbers as spatial volumes or as locations along a path (Núñez & Marghetis, in press). When people talk about "tiny numbers," they perform pinching gestures; when they talk about "high numbers," they point upwards (Winter et al., 2014). Even mathematical experts working on proofs produce gestures that reflect mappings between real numbers and space, as proposed by CMT (Marghetis & Núñez, 2013).

According to CMT, conceptual metaphors consist of directional, asymmetric mappings from source (e.g., space) to target domains (e.g., number, time) rather than symmetrical associations between domains (Lakoff, 2008; Lakoff & Johnson, 1980). Proponents of CMT argue that this *conceptual* asymmetry is responsible for analogous asymmetries in language and behavior (cf. discussion in Casasanto & Boroditsky, 2008). For instance, the language of space is re-used for time and number, while the language of time and number are used less frequently to describe space; we talk of looking *forward* to the future but would never ask someone to look to the *future* if we wanted them to look forward spatially. Though it is possible to talk about space in terms of time, as in "*we're only a few minutes away from the subway*" (Casasanto & Boroditsky, 2008: 590), talking about time in terms of space is more frequent.

Compared to ATOM, which emphasizes evolution, CMT emphasizes the role of experience and culture during ontogeny. For example, the metaphor MORE IS UP captures a statistical regularity in experience: as quantity increases, so does height. As peanuts are poured onto a table, they pile up; as water is poured into a glass, the water level rises (Lakoff, 1987: 276). Similar experiential connections exist for space and time, particularly during physical movement (e.g., elapsed time correlates with distance traveled). According to CMT, these experiential regularities cause individuals to link the domains in their minds—that is, to create conceptual metaphors (Grady, 1997; Lakoff, 2008, 2012; Lakoff & Johnson, 1999). These conceptual links, in turn, are argued to drive the historical and developmental emergence of more abstract uses of spatial language, such as *Housing costs are rising* or *The meeting is taking a long time*. In addition to these experiential origins, contemporary CMT theorists additionally argue that metaphorical linguistic expressions not only reflect existing conceptual metaphors but also support their initial development (e.g., Boroditsky, 2001; Casasanto, 2008b).

2.3. *The inter-dependence and independence of domains*

Both ATOM and CMT describe cross-domain interactions between space, time, and number. However, it should be pointed out that neither proposal claims that the neural or mental representation of these domains is exhausted by their overlap. Time is associated with its own phenomenology and linguistic structures (Evans, 2004), and its cognitive processing depends on its own neural machinery (Buhusi & Meck, 2005), including the cerebellum (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002) and supplementary motor areas (Macar et al., 2002), among others. Similarly, for space and number, single-cell recording studies with monkeys show that even though some neurons are tuned to both number and length simultaneously, others are tuned specifically to either number or length alone (Tudusciuc & Nieder, 2007; cf. discussion in Nieder & Dehaene, 2009). Thus, even though the domains of space, time, and number are interconnected and rely on shared neural machinery—as predicted by both CMT and ATOM—they each also involve distinct structures, properties, and neural substrates. ATOM proposes a shared neural substrate for representing magnitudes, but also allows that the representation of spatial, numerical, and temporal magnitudes may involve additional domain-specific neural circuits. Similarly, though CMT argues that we conceptualize time and number in terms of space, it is not committed to a complete reduction of time and number to space.

3. Asymmetry: between what, when, and why?

On a first pass, ATOM and CMT agree on a core claim: that the conceptual domains of space, time, and number are tightly linked. But from this common ground springs a number of disagreements. At a superficial level, for instance, the theories differ in their disciplinary ties, and the previous section attempted to bring together the disparate sources of evidence invoked to support each theory.

Less superficially, the two theories make different commitments to the relative strengths of influences between domains. CMT argues explicitly that conceptual metaphors are *asymmetrical*, with one domain having a greater influence on the other domain, compared to the other way around (cf. Casasanto & Boroditsky, 2008; Lakoff & Johnson, 1980, 1999; Merritt et al., 2010). Even though ATOM is not in principle *opposed* to cross-domain asymmetries (Bueti & Walsh, 2009), it is typically interpreted as predicting symmetrical mappings between domains (e.g., Merritt et al., 2010). For example, Bonato et al. (2012) argue that "ATOM is more concerned with a bidirectional overlap of magnitudes." The two theories, therefore, appear to differ in their commitment to *asymmetries*. In this section, we clarify the notion of asymmetry, introducing a number of important conceptual distinctions.

We begin with a few preliminary conceptual clarifications. First, the issue is not about whether effects are unidirectional or bidirectional (e.g., whether number influences space, space influences number, or both), but whether admittedly bidirectional influences are symmetric or asymmetric (cf. Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008). CMT and ATOM agree that cross-domain influences are most likely bidirectional. English speakers, for instance, *do* occasionally use time to talk about space (e.g., saying "*ten minutes away*" to describe a distance). Thus, even the linguistic evidence supports bidirectional links between domains.

Second, we distinguish two notions of asymmetry, *Domain Asymmetry* and *Directional Asymmetry*. By Domain Asymmetry we mean the issue of whether particular domains are more likely to exhibit interactions than others. According to *Domain Symmetry*, *all* domains are equally likely to exhibit interactions with other domains. According to *Domain Asymmetry*, some domains are more likely than others to exhibit interactions. The domain of space, for instance, may be especially promiscuous in its cross-domain interactions because it often serves as the "source" domain for more abstract domains like number and time. This will be discussed in §3.1. By Directional Asymmetry we mean the issue of whether, for a pair of domains (e.g., space and time), the strength of influence from one domain to another is equal or unequal to the strength of influence in the other direction, an issue we take up in §3.2. For instance, spatial cues may have a larger effect on temporal judgments than temporal cues do on spatial judgments (Casasanto & Boroditsky, 2008). These two forms of asymmetry—domain and directional—are largely orthogonal, and CMT and ATOM make distinct predictions for each type of asymmetry.

3.1. *Domain asymmetry and symmetry*

At least on *a priori* grounds, ATOM predicts interactions between *all* magnitude-related domains. By contrast, CMT invokes mappings between source and target domain to explain cross-domain interactions, and thus predicts interactions between target domains and their source (e.g., space–number and space–time interactions) but not necessarily between one target domain and another (e.g., number–time interactions).

At the linguistic level, the language of space is commonly used to describe other domains, time and number in particular (Alverson, 1994; Haspelmath, 1997; Lakoff & Johnson, 1980; Lakoff & Núñez, 2000; Sweetser, 1991; Traugott, 1978). On the other hand, there are few linguistic connections between numerical and temporal magnitudes. In the few cases where lexical items are shared between number and time (e.g., numerical and temporal intervals alike can be *long* or *short*), the lexical items have been extended from an original spatial sense (Alverson, 1994; Haspelmath, 1997; Sweetser, 1991; Traugott, 1978). At the linguistic level, therefore, there appears to be Domain Asymmetry, as predicted by CMT.

However, there is perceptual, conceptual, and neural evidence of Domain *Symmetry*: in addition to number–space and time–space interactions, predicted by both CMT and ATOM, there are also interactions between number and time, predicted only by ATOM. For example, when Arabic numerals are displayed visually, their numerical magnitude influences judgments of their temporal duration (Alards-Tomalin, Leboe-McGowan, Shaw, & Leboe-McGowan, 2014; Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007), and vice versa (Roitman, Brannon, Andrews, & Platt, 2007). Moreover, when two Arabic digits are presented and participants are asked to estimate duration, participants are more accurate when small numbers are paired with short durations and large numbers with long durations (Xuan et al., 2007). Duration discrimination is affected by the number of particular stimuli presented, in both humans (Balci & Gallistel, 2006) and rats (Meck & Church, 1983). Even zero-to three-day-old human neonates spontaneously associate the domains of space, time and number (de Hevia et al., 2014).

Symmetric interactions exist also at the level of conceptualization. We can construe numerical sequences, for instance, as temporal processes that unfold over time (Langacker, 1990, chap. 5). When asked the ambiguous time question ("Next Wednesday's meeting has been moved forward two days. When is it now that it has been moved forward?"), Matlock et al. (2011) found that counting forward along a number sequence primes Friday responses and counting backwards primes Monday responses, as if numerical change were influencing reasoning about temporal change. In this case, however, common spatial representations of time and number might act as a mediating factor. Using a more implicit measure, Kiesel and Vierck (2009) had participants determine the parity (even versus odd) of single digit numbers and respond by pressing a button for either a short or a long duration. Responses were faster when the response duration was congruent with the number's magnitude—a temporal version of the classic SNARC effect (Dehaene et al., 1993). Finally, numerosity and duration discrimination activate overlapping brain structures, in particular the right intraparietal cortex (sIPC) and inferior frontal gyrus (IFG) (Hayashi et al., 2013).

There is compelling evidence, therefore, that time and number interact perceptually, conceptually, and neurally (cf. discussion in Bonato et al., 2012). This Domain Symmetry is a natural prediction of ATOM, which, at first blush, places magnitude-related domains on equal footing. It does not follow naturally from CMT, on the other hand, which does not posit conceptual metaphors like TIME IS NUMBER or NUMBER IS TIME.

The fact that space, time, and number all interact with each other does not entail that all magnitudes are equal (cf. Bueti & Walsh, 2009: 1833). There is evidence to suggest, for example, that the link between space and time is tighter than the links between other magnitude-related domains, such as space and loudness, or space and luminance (Bottini, Guarino, & Casasanto, 2013; Srinivasan & Carey, 2010). And number may be more tightly connected to space than to other domains; there is more overlap in neural activation for number and size, for instance, than for number and luminance (Pinel et al., 2004). These findings are consistent with ATOM. The magnitude system is specialized for coordinating action, according to ATOM, and space and time are more systematically conflated during action (e.g., movement) than other pairs of domains, such as space and loudness or space and luminance (Bueti & Walsh, 2009; Walsh, 2003).

3.2. Directional asymmetry and symmetry

Do space, time, and number interact symmetrically, with equal influences of, say, space on time and also of time on space? Alternatively, might space structure people's understanding of time and number more so than these domains structure our understanding of space? Proponents of CMT argue for the latter view, here called *Directional Asymmetry*.

On one level, Directional Asymmetry is a phenomenon of language, including both current use and historical change. A word like “long,” for example, can be used for numerical intervals and temporal durations, but its primary sense is spatial (cf. Lakoff & Johnson, 1980). But CMT claims to be a theory of thought, not just of language, and thus seeks to explain linguistic asymmetries in terms of underlying *conceptual* asymmetries (Casasanto & Boroditsky, 2008). At an even more basic level, the *perceptual* interactions between space, time, and number may be asymmetrical, such that spatial properties of a percept should have more of an influence on temporal or numerical judgments about that percept, compared to the other direction of influence. The Directional Asymmetry predicted by CMT, therefore, could manifest itself differently at the levels of language, conceptualization, or perception.[1]

Empirical support for Directional Asymmetry varies widely across levels. At the linguistic level, Directional Asymmetry is relatively uncontroversial (see Kövecses, 2002). As mentioned above, people sometimes use temporal language to talk about space, but this occurs less often and less systematically than the reverse.[2] Moreover, historical semantic change typically occurs in the direction of proposed metaphorical mappings, with words that express concepts from the source domain only later acquiring additional senses in the target domain (Alverson, 1994; Evans, 2004; Haspelmath, 1997; Lakoff, 1993; Sweetser, 1991). For example, “before” and “after” can now describe temporal relations; originally they were reserved for spatial relations (Traugott, 1978). The converse seldom happens: temporal words such as “time,” “noon,” or “day” have not developed spatial meanings over the course of language history.

There is also evidence of Directional Asymmetry at the conceptual level. In practical terms, conceptual Directional Asymmetry predicts that spatial concepts should prime temporal ones, more than temporal concepts prime spatial ones. Confirming this prediction, Boroditsky (2000) reported asymmetric interactions between spatial and temporal relations: priming spatial relations affected subsequent temporal reasoning, but priming temporal relations did not reliably affect subsequent spatial reasoning.

Thus, for language and reasoning, there is evidence of Directional Asymmetry. What about lower-level processes? Here, too, asymmetry may exist. When growing lines are displayed visually, spatially longer lines are judged to have been displayed for a longer duration, but presentation duration does not affect judgments of spatial length (Casasanto & Boroditsky, 2008). This perceptual asymmetry appears in humans as early as four to five years of age (Bottini & Casasanto, 2013; Casasanto et al., 2010). Duration judgments are affected not only by spatial properties of meaningless stimuli, but even by the semantics of words: the perceived duration of words that imply short lengths, such as *pencil*, are judged to be shorter than words that imply long lengths, such as *footpath* (Bottini & Casasanto, 2010a, 2010b). Here again, there is evidence for Directional Asymmetry: Varying the implied duration of words describing events (e.g., *blink* versus *season*) did not affect judgments of the words' lengths (Bottini & Casasanto, 2010a, 2010b).

There are also Directional Asymmetries between space and *number*. Using a variant of the Stroop task, Dormal and Pesenti (2007) showed that spatial cues affected number processing, while numerical cues did not interfere with spatial processing. Similarly, Hurewitz, Gelman, and Schnitzer (2006) found that changes in physical size affected numerical estimates, but changes in quantity did not affect size judgments. Similar asymmetries have been documented between number and *time*, with number influencing duration judgments but not vice versa (Brown, 1997; Cappelletti, Freeman, & Cipolotti, 2009; Droit-Volet, Clement, & Fayol, 2003).

There is considerable evidence, therefore, of selective influences of the putative ‘source’ domain of space on ‘target’ domains of number and time, without corresponding influences in the other direction. At the same time, however, there is extensive evidence of genuinely *bidirectional* influences, with number and time also influencing space. For example, the magnitude of task-irrelevant numbers biases length estimates, in both adults (de Hevia, Girelli, Bricolo, & Vallar, 2008) and 3– to 5-year-old children (de Hevia & Spelke, 2009), and the magnitude of task-irrelevant numbers orients spatial attention (e.g., Fischer, Castel, Dodd, & Pratt, 2003). Moreover, in the classic Tau effect (e.g., Benussi, 1913; Helson, 1930; for review, see Jones & Huang, 1982), the elapsed duration between two discrete light flashes affects judgments of the distance between the light flashes (see, however, the discussion in Bottini & Casasanto, 2013). And, if a spatially large visual stimulus is presented for a short duration, it appears equal in size to a smaller visual stimulus presented for a longer duration (Bill & Teft, 1969, 1972). There also is evidence for bidirectional interactions between number and time: The magnitude of a visually presented numeral influences judgments of its presentation duration (Alards-Tomalin et al., 2014; Oliveri et al., 2008; Xuan et al., 2007), while presentation duration influences judgments of numerosity (Roitman et al., 2007; but see Droit-Volet et al., 2003).

This reflects a more general phenomenon in which directional cross-domain mappings predicted by CMT turn out to exhibit bidirectional experimental effects. Priming physical distance affects social judgments (Williams & Bargh, 2008b),

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[1] These “levels” are not meant to be exhaustive or mutually exclusive, nor are they meant to differ discretely. Many researchers have suggested a continuum among levels (e.g., Barsalou, 1999).

[2] Symmetric linguistic patterns are found mostly when relations between domains are tightly constrained by context (Lakoff & Johnson, 1999). For example, if asked the distance between San Diego and Los Angeles, one can reply “two hours by car,” invoking time to respond to a question about space. This works because in this context, the passage of time is directly connected with spatial displacement (see also, Evans, 2013, chap. 7).

but manipulating social distance also affects spatial responses (Matthews & Matlock, 2011). Experiencing physical warmth promotes social warmth (Williams & Bargh, 2008a), but experiencing social warmth also influences the perception of room temperature (Zhong & Leonardelli, 2008). Bidirectional behavioral effects have been found for the metaphors HAPPY IS UP (Casasanto & Dijkstra, 2010; Crawford, Margolies, Drake, & Murphy, 2006), BAD IS DARK (Meier, Robinson, & Clore, 2004; Meier, Robinson, Crawford, & Ahlvers, 2007) and SIMILARITY IS PROXIMITY (Casasanto, 2008a; Pecher & Boot, 2010; Winter & Matlock, 2013). So, for numerous mappings proposed by CMT, linguistic asymmetries are accompanied by bidirectional interactions in behavior (see also Landau, Meier, & Keefer, 2010).

The studies reviewed above demonstrate that manipulating the metaphorical source domain (e.g., space) can effect the target domain (e.g., time), and manipulating the target domain can effect the source. Recall, however, that the critical issue that separates ATOM and CMT is not unidirectionality, *per se*, but Directional Asymmetry, differences in the *strength* of the influence of one domain on the other. Few studies have directly addressed this critical issue, perhaps because cross-domain differences in factors like discriminability, stimuli, salience, or stability make it difficult to determine the relative strengths of bidirectional influences. The experiments in Casasanto and Boroditsky (2008), and their follow-ups (Bottini & Casasanto, 2013; Casasanto et al., 2010; Merritt et al., 2010), are among the only studies to specifically assess Directional Asymmetry as opposed to unidirectionality. Recall that Casasanto and Boroditsky (2008) found that effects of spatial length on temporal duration were much larger than any effects of temporal duration on length. They explicitly addressed the issue of discriminability, by verifying that discriminability was similar for both spatial length and temporal duration. They also ruled out any effect of stimulus type by using identical stimuli (lines) for both the length judgments and the temporal duration judgments. Finally, in one of their experiments, they increased the salience of temporal duration by accompanying the stimuli with a sustained tone, which has duration but not spatial extent. Even with this additional temporal cue, there remained Directional Asymmetry, with spatial length still exerting a greater influence over temporal duration. These results are some of the clearest evidence for Directional Asymmetry.

Nevertheless, even these studies face interpretative difficulties. In Casasanto and Boroditsky's (2008) extending lines paradigm, task demands may have created an imbalance between the spatial and the temporal dimension. To determine length, participants could rely on their memory of the expanding line's final state alone; to perceive time, participants had to integrate over time, comparing the line's onset to its final state. As noted by Morgan, Giora and Solomon (2008), “the critical difference between estimates of temporal length and estimates of spatial length seems to be that the former can only be made at the end of the exposure” (cf. discussion in Bonato et al., 2014: 2267). To address this concern, Casasanto and Boroditsky (2008, Experiment 5) included a moving dot rather than an extending line, so that the final line length would not be visible “at glance.” However, even in this case participants could determine the approximate length of the dot's movement from its final location, since the dot always began in the same approximate region of the computer screen (with some random jitter). Thus, participants had to recall and compare the start and end of each trial to perform the duration estimation but not for the distance estimation.[3] In the end, the dearth of studies that test directly the asymmetry of cross-domain interactions may be due to the difficulties posed by ruling out all these confounds.

Even if directional asymmetries *were* incontrovertibly demonstrated, this would not necessarily contradict more nuanced versions of ATOM. Though the theory is often taken to predict bidirectional and symmetric associations between domains (Bottini & Casasanto, 2010b; Bottini & Casasanto, 2013; Casasanto et al., 2010), ATOM's proponents have replied that “all magnitudes are not created equal” (Bueti & Walsh, 2009: 1833). Although the ATOM framework does not explicitly *predict* cross-domain asymmetries, or the particular form they might take, it is in principle compatible with directional asymmetries that derive from differences in the domains themselves (Bueti & Walsh, 2009).

In sum, the evidence for Directional Asymmetry is mixed. The strongest evidence for asymmetry is at the linguistic level. It should be noted, however, that these linguistic asymmetries might have alternative explanations that do not have to do with neural or cognitive asymmetries. For instance, linguistic asymmetries may derive from speakers' urge to talk about things that are shared with listeners (Gerrig & Gibbs, 1988; Thibodeau & Durgin, 2008), that are within their common ground (Clark, 1996). On this account, speakers may use familiar notions as linguistic source domains because they are more likely understood or experienced by all parties. The visual, tangible, and sharable character of the spatial domain might make it especially salient for novel metaphorical expressions. Hence, there are proposals within linguistics that can explain linguistic asymmetry without recourse to underlying conceptual or perceptual asymmetries.

Directional Asymmetry at the perceptual or conceptual levels are less reliable than asymmetries at the linguistic level but nevertheless attested. Where might they come from? CMT proposes that conceptual metaphors derive from experiential correlations (e.g., between size and quantity, or distance and time spent traveling). Lakoff (2008, 2012) invokes Hebbian learning (“neurons that fire together wire together”) (Hebb, 1949) as the principle that leads from experiential correlations to cross-domain mappings. For example, for the mapping of quantity onto verticality, the repeated co-occurrence of verticality and quantity in the real world means that neural populations responsible for processing verticality and quantity may repeatedly become activated together or in close temporal succession, ultimately leading to neural connections between these two domains. Although Hebbian learning is a plausible mechanism for making two mental domains

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[3] This asymmetry in the difficulty of the task (integration *vs* no integration) also applies to the imaging study by Gissjels, Bottini, Rueschemeyer and Casasanto (2013), who found that when participants perform the growing lines task, regions within the inferior parietal cortex that become activated for both temporal and spatial judgments are more strongly activated for the temporal than for the spatial task.

connected, it is not straightforward to show that this causes asymmetries between domains.[4] In general, if, as claimed by CMT, mappings between space, time and number do stem from experience, then the theory needs to explain how statistical correlations that are inherently symmetrical get turned into neural and conceptual asymmetries. Or, in other words: What specifically in the experience of correlations between space, time and number makes space primary?[5]

3.3. *Evaluating asymmetry*

Having clarified and evaluated the issue of asymmetry, we are now better situated to evaluate the commitments of ATOM and CMT. The two theories do not only make different predictions about the direction of the influence between domains (Directional Asymmetry), but also disagree about which domains should have interactions in the first place (Domain Asymmetry). Fig. 1 gives a schematic display of the two theories' views of cross-domain interactions. The *direction* of the arrows indicates the direction of predominant influence and thus corresponds to predictions about Directional Asymmetry. *Which* domains are connected corresponds to predictions about Domain Asymmetry.

Our review of the literature suggests that both CMT and ATOM have explanatory strengths and weaknesses. As predicted by ATOM, bidirectional influences in perception and action seem the rule rather than the exception. However, for many of these, we do not have sufficient evidence to assess the claim of Directional Asymmetry, whether the influence of one domain is stronger than the influence of the other domain. The clearest demonstrations of Directional Asymmetry have been for TIME IS SPACE metaphors (Bottini & Casasanto, 2013; Casasanto & Boroditsky, 2008; Casasanto et al., 2010; Gissjels et al., 2013; Merritt et al., 2010). However, to buttress the case for Directional Asymmetry due to asymmetric conceptual mappings, as proposed by CMT, research on space–time interactions needs to be completed by similarly controlled experiments for other relevant domains, such as space and number. On the other hand, ATOM theorists must clearly articulate when and why particular domains will have a stronger influence than others.

When it comes to Domain Symmetry, there are clear demonstrations of interactions between number and time (Balci & Gallistel, 2006; Brown, 1997; Dormal, Seron, & Pesenti, 2006; Kiesel & Vierck, 2009; Matlock et al., 2011; Oliveri et al., 2008; Vicario et al., 2008; Xuan et al., 2007; see review in Bonato et al., 2014: 2267–2268), which ATOM predicts but CMT does not. One way for CMT to account for these results is to claim that number–time interactions are mediated by a common spatial schema, such that the target domains of number and time become entangled through their shared source domain of space. Future empirical work will need to investigate whether there is actually evidence that spatial representations mediate established interactions between number and time.

4. Magnitudes or relations?

ATOM is about *magnitudes*, whereas CMT is about *relations* between conceptual elements. This critical difference is often overlooked. Space, time and number are complex conceptual domains, replete with diverse elements: numbers that are even and odd, prime and composite; events that vary in duration and order; places that vary in location and extent. These elements do not stand alone but are organized into complex webs of relations: numbers are greater and less than each other, and composite numbers can be decomposed into prime factors; events can be nested or overlapping; objects can be on or in each other, adjacent or distant, and their location can be described relative to a speaker or to external landmarks like cardinal directions.

When it comes to time, for instance, our concepts go far beyond simple magnitude-based concepts of duration. We deploy multiple, complementary spatial models to understand the passage of time (i.e., future, past) and temporal relations (e.g., earlier, later) (for a review, see Núñez & Cooperrider, 2013). Recall that English has two ways to describe time relative to "now," associated with different patterns of reasoning: either with the speaker moving while time stands still (e.g., "*We are approaching the holidays*"), or with time moving while the speaker stands still (e.g., "*The holidays are approaching*"). Rather than focusing on magnitude, these metaphors foreground temporal order, change, and perspective. Indeed, our understanding and phenomenology of time is complex and nuanced (Evans, 2004, 2013).

The domain of space, too, involves more than spatial magnitudes. Our conceptualization of space operates against a backdrop of multiple frames of reference, relative to which we reason and talk about objects and locations (Kemmerer, 2006; Levinson, 2003). Even simple "topological" relations like *in*, *on*, or *outside* are beyond the scope of a theory that deals solely with magnitudes. As a result, ATOM is only capable of accounting for a small slice of any cognitive domain—the slice that deals with magnitudes. This is not meant as a criticism but as a clear statement of the theory's limitations. Whatever role is played by the domain-general magnitude system posited by ATOM, it will never be the whole story of the conceptual organization of space, time, and number. For example,

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[4] Lakoff (2012) speculatively invokes spike-time-dependent synaptic plasticity (STDP, Song, Miller, & Abbott, 2000) to explain asymmetry at a neural level. With STDP, the relative timing of pre- and post-synaptic potentials matters. That is, only those connections are strengthened where there was a presynaptic potential that occurred shortly before the postsynaptic potential. Other connections are weakened. However, it is not clear at all that STDP can actually create the particular Directional Asymmetries proposed by CMT. In the case of asymmetrical space, time and number interactions, for example, this would require that neural clusters associated with spatial processing be repeatedly activated *before* connected neural clusters associated with time and number. Moreover, this activation would need to occur in a tightly coupled fashion. The current experiential accounts for cross-domain mappings in CMT are not sufficiently detailed to allow predictions for the temporal asymmetries needed to invoke STDP as an explanation of Directional Asymmetry.

[5] Some linguists have begun to analyze metaphors that are based on experiential correlations as metonymies (e.g., Barcelona, 2000; Radden, 2002; Kövecses, 2013), which are "within-domain" mappings that are not necessarily asymmetrical.

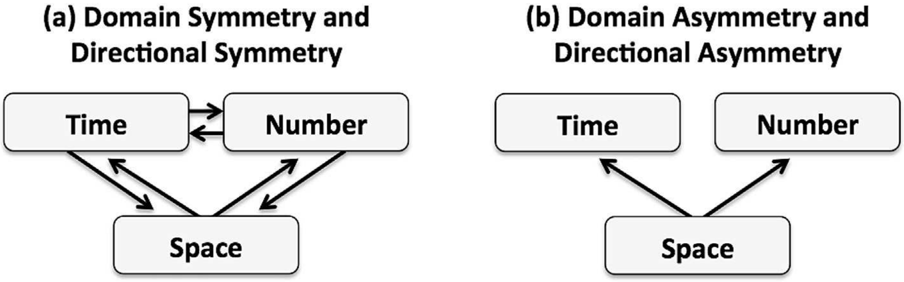

Fig. 1 – Directional and Domain Asymmetry for the domains of space, time and number. Arrows indicate predicted influences between domains. We view ATOM as being most consistent with (a), and CMT with (b).

ATOM seems incapable of accounting for the specific finding that cultures that habitually use landmarks for spatial descriptions sometimes deploy that same frame of reference when reasoning about time, associating earlier and later with east and west (Boroditsky & Gaby, 2010) or past and future with downhill and uphill (Núñez, Cooperrider, Doan, & Wassmann, 2012). Though these phenomena involve mappings between space and time, these are mappings between systems of linguistically and culturally determined *relations*, not between magnitudes.

The distinction between relations and magnitudes calls into question whether ATOM can account for associations between spatial *locations* and number or time (e.g., Dehaene et al., 1993; Vicario et al., 2008). As discussed above, proponents of ATOM sometimes invoke these effects as supportive evidence, instances of a generalized SQUARC effect (Bueti & Walsh, 2009; Walsh, 2003). It is unclear, however, how to interpret these locational findings in terms of magnitudes. At the bare minimum, ATOM needs to invoke additional assumptions to explain locational effects. For instance, proponents of ATOM could posit that numbers are automatically interpreted as distances from an origin, and that—among Western adults—the origin is reliably placed to the left. ATOM requires a similar story for vertical locational effects (Hartmann et al., 2011; Ito & Hatta, 2004; Loetscher et al., 2010; Schwarz & Keus, 2004; Shaki & Fischer, 2012). It is less clear how ATOM could accommodate associations between temporal concepts and the back–front axis, where neither future or past, nor back or front, are necessarily *more* or *less* than each other.

In contrast, from its inception CMT has been concerned with complex relations. The cross-domain mappings that constitute a conceptual metaphor do not operate only between elements—between spatial length and temporal duration, for instance—but also between relations and inferences. Recall the ambiguous time question ("Wednesday's meeting has been moved ahead…"). Respondents' reasoning about the meeting's new time was influenced by the particular perspective that they adopted (ego-moving versus time-moving)—that is, by the conceptual metaphor they used to reason about the scenario. In both metaphors, days are associated with locations, and temporal rescheduling is associated with changes in location. What differs is the *inferences* afforded by the metaphors, inferences that produced distinct answers (Monday *vs* Friday). In terms of scope, therefore, CMT is able to account for a broader range of cognitive phenomena than ATOM, from simple associations between elements (e.g., lengths and durations) to mappings that involve rich systems of inference (e.g., spatial rearrangements of objects and the temporal rearrangement of events).

5. Directions for unification

The next generation of research on space, time, and number within cognitive neuroscience, we suggest, will draw on the strengths of both these approaches to account for the full breadth of cross-domain interactions—from magnitude-based interactions in perception, to complex spatial models in language and abstract reasoning.

5.1. *Scaling up from magnitudes to metaphors*

Macaques show bidirectional, symmetric interactions between the perception of space and time (Merritt et al., 2010), while human neonates associate space, time and number within the first few hours after birth (de Hevia et al., 2014; see also de Hevia & Spelke, 2010; Lourenco & Longo, 2010, 2011; Srinivasan & Carey, 2010). This suggests one possible connection between the two theories: The selective, directional, and asymmetric mappings discussed by CMT might build on biologically determined, symmetric connections between space, time and number (see also Casasanto et al., 2010; de Hevia, Girelli, & Cassia, 2012; Merritt et al., 2010; Srinivasan & Carey, 2010). Building on these inherited intuitions, cross-domain mappings in adults may gradually reflect the asymmetry of linguistic metaphors (Boroditsky, 2001; Fuhrman et al., 2011; for review, see Casasanto & Bottini, 2014) and cultural practices such as writing (Shaki et al., 2009) and visual depictions (Tversky, 2011). Thus, asymmetric metaphors like TIME IS SPACE may build on symmetric, inherited intuitions. These more selective, directional mappings may emerge over the course of development as a result of various factors: the statistics of the natural world (e.g., verticality correlated with quantity; duration correlated with displacement); differences in perceptual acuity (e.g., more precision in estimating space than time or number); habitual interaction with cultural artifacts (e.g., timelines, number-lines); or cultural practices, including language and gesture.

The domain-general magnitude system posited by ATOM may favor the development of specific metaphorical mappings over others (cf. discussion in Srinivasan & Carey, 2010). The representational overlap of space, number and time in early development (de Hevia et al., 2014; de Hevia & Spelke, 2010; Lourenco & Longo, 2010; Srinivasan & Carey, 2010) might help children extend lexical meanings from spatial uses to other senses (e.g., from "long length" to "long time") (Srinivasan & Carey, 2010: 238). Conversely, novel linguistic descriptions of time or number that use spatial language might be intuitively comprehensible in virtue of a pre-existing magnitude system, which may account for the historical development of conventional linguistic metaphors.

Finally, in some cases, culture and language might even override existing cross-domain magnitude interactions. Casasanto (2008b) investigated the temporal concepts of English speakers, who talk about time in terms of *length*, and Greek speakers, who talk about time in terms of *amount*. The length of spatial stimuli influenced English but not Greek speakers' temporal judgments; conversely, animations of changing *amount* influenced Greek but not English speakers' temporal judgments. Habitual use of specific metaphorical expressions might reinforce particular cross-domain mappings (cf. discussion in Casasanto, 2014), while suppressing some of the more general associations described by ATOM.

ATOM and CMT might then reflect cross-domain interactions that develop over different time-scales, with ATOM focusing on phylogeny and CMT focusing on ontogeny. The evolutionarily older magnitude system in parietal cortex posited by ATOM might be subject to neural reuse or recycling as a result of culture and experience (Anderson, 2010; Dehaene & Cohen, 2007), shaped throughout ontogeny by cultural artifacts and practices—including language and writing—to produce more directional, asymmetric mappings. This process of developmental elaboration may be necessary for mappings that involve spatial location, direction, and other relations addressed by CMT, rather than the simple but foundational magnitudes addressed by ATOM. On this account, ATOM and CMT are complementary rather than contradictory. A generalized magnitude system may be the evolutionary and developmental substrate that helps scaffold more complex and culturally specified concepts.

5.2. *Functional relevance of cross-domain mappings*

The two theories offer complementary perspectives on the functional relevance of cross-domain associations. CMT has traditionally argued for a multiplicity of roles across various arenas: reasoning, language comprehension, early concept acquisition and semantic change, to name a few (e.g., Lakoff, 1993; Lakoff & Núñez, 2000). ATOM, by contrast, proposes that a domain-general magnitude system is adaptive for guiding *action*, and thus ties interactions between space, number, and time to the skillful control of situated activity (Bueti & Walsh, 2009). Moreover, since space, time, and number are often correlated in the natural world, a domain-general representation of magnitude could play a role in learning environmental regularities and predicting one dimension from another (Lourenco & Longo, 2011). When it comes to the functional relevance of cross-domain interactions, these theories highlight different ways that cross-domain mappings might play a functional role.

There is evidence that cross-domain mappings do actually play a functional role in reasoning, understanding, and development. For example, spatial skills have long been known to predict mathematical success (Uttal, Miller, & Newcombe, 2013; Wai, Lubinski, & Benbow, 2009). Gunderson, Ramirez, Beilock, and Levine (2012) found that this connection was mediated by the ability to map numbers to locations along a linear spatial path. Lonnemann, Krinzinger, Knops, and Willmes (2008) furthermore found that, at least for 8- and 9-year-old boys, cognitive interactions between space and number predict their calculation abilities. Moreover, educational interventions that explicitly train the mapping between numbers and spatial locations have been found to improve numerical understanding (Ramani & Siegler, 2008; Siegler & Ramani, 2008, 2009; Uttal, Meadow, et al., 2013; Wilson, Dehaene, et al., 2006; Wilson, Revkin, et al., 2006). These results suggest that conceptual mappings between number and spatial location are causally implicated in the early development of mathematical understanding.

But the evidence is not cut and dry. Recently, for instance, Cipora and Nuerk (2013) found no relation between the size of an individual's SNARC effect and their mathematical expertise, as measured by an algebra task. This leaves open the possibility that the spatial–numerical association captured by the SNARC effect does play a role, but in concert with other spatial associations—such as associations between space and arithmetic (e.g., Knops et al., 2009; Marghetis et al., 2014) or algebraic structure (e.g., Goldstone, Landy, & Son, 2010; Schneider, Marayuma, Dehaene & Sigman, 2012).

6. Conclusions

CMT argues that interactions between space, time and number reflect sophisticated cross-domain conceptual mappings, mappings that allow us to understand time as motion relative to the ego, numbers as locations along a path, and more. These metaphors may build on and expand the more general magnitude system proposed by ATOM. Both theories predict that different magnitudes should rely on shared cortical circuits. While ATOM correctly predicts Directional and Domain Symmetries, CMT highlights the complex chains of reasoning captured by conceptual metaphors, the role that such metaphors may play in higher cognitive processing, and the resulting directionalities and asymmetries. Together, the two theories shed light on different aspects of the complex interconnections between space, time and number.

By combining the insights and interests that drive both ATOM and CMT, we are better situated to integrate a broad range of phenomena. Consider, for example, how many languages use spatial terms to describe number and time. It would be surprising if this systematic, ubiquitous linguistic recycling of spatial language were unrelated to the neural and cognitive resources that are shared by space, time, and number. A hybrid account allows us to explore connections between low-level and high-level processes. For example, we can investigate developmental changes in Directional or Domain Symmetry, perhaps concluding that asymmetry increases throughout ontogeny (cf. discussion in Srinivasan & Carey, 2010), or that more complex cross-domain interactions involving locations or inferences require extensive linguistic or cultural scaffolding (e.g., Mills, Rousseau, & Gonzalez, 2014). Or we can systematically investigate, for a pair of domains, how Directional Asymmetry may differ across levels of human behavior, from simple perceptual processing to complex linguistically mediated conceptual reasoning. Or we can investigate, not just differences but *influences* between processing levels; given rampant Directional Asymmetry in linguistic constructions, we might, for example, expect that priming language might amplify latent or weak asymmetries at the conceptual or perceptual levels. Finally, we can articulate targeted accounts of interactions at the perceptual, conceptual, and linguistic levels, without trying to force a single framework to account for cross-domain interactions in all of human behavior and thought. Moreover, CMT's emphasis on Directional Asymmetry between domains calls for investigating the neural mechanism that underlie these asymmetries, a topic that only a few studies have begun to address (Gijssels, Bottini, Rueschemeyer, & Casasanto, 2013).

Both ATOM and CMT emphasize the benefits of these cross-domain mappings. When first articulating ATOM, Walsh (2003) lamented that the early developmental literature on numerical cognition tended to view the number-space associations as obstacles rather than benefits. Bryant and Squire (2001) noted that developmental psychologists have viewed space as “part of the problem in children's mathematics, not part of the solution.” If ATOM is right, however, cross-domain associations may not be a disadvantage during learning, a cognitive crutch, but rather a beneficial part of our evolutionary inheritance, functionally relevant for the coordination of action. On this count, CMT is in agreement. From its outset, CMT has viewed spatial mappings as foundational to more abstract reasoning and understanding. Hence, together, ATOM and CMT highlight how the interweaving of space, time, and number in the human mind may form a fabric that supports thought, from low-level perception to the acquisition of complex concepts.

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