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Review

When time is space: Evidence for a mental time line

Mario Bonato*, Marco Zorzi, Carlo Umiltà

Department of General Psychology and Center for Cognitive Science, University of Padova, Padova, Italy

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A B S T R A C T

Time and space are tightly linked in the physical word. Recently, several lines of evidence have suggested that the mental representation of time might be spatial in nature. For instance, time–space interactions have been described as a strong preference to associate the past with the left space and the future with the right space. Here we review the growing evidence of interactions between time and space processing, systematized according to the type of interaction being investigated. We present the empirical findings supporting the possibility that humans represent the subjective time flow on a spatially oriented "mental time line" that is accessed through spatial attention mechanisms. The heterogeneous time–space interactions are then compared with the number–space interactions described in the numerical cognition literature. An alternative hypothesis, which maintains a common system for magnitude processing, including time, space, and number, is also discussed. Finally, we extend the discussion to the more general issue of how the representation of these concepts might be grounded into the cortical circuits that support spatial attention and sensorimotor transformations.

Contents

* Corresponding author at: Department of General Psychology, Via Venezia 8, 35131, Padova, Italy. Tel.: +39 (0) 498276642.
E-mail address: mario.bonato@unipd.it (M. Bonato).

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The biggest difference between time and space is that you can't reuse time.

Merrick Furst

The study of time perception and representation has long been tackled in the past by philosophers and, more recently, also by cognitive (neuro)scientists (Wittmann and van Wassenhove, 2009; Dehaene and Brannon, 2010). Thus, the contemporary approach to the study of time processing and representation is highly interdisciplinary and it includes psychophysical, evolutionary, and neurobiological perspectives. Our aim here is to selectively and systematically review the recent studies that explored the spatial characteristics of time processing and, more in general, the interactions between time, space, and quantities. We will first focus on the evidence supporting the presence of a representation of time with spatial characteristics, i.e. a “mental time line”. Then, we will broaden our focus discussing other types of interactions between magnitudes.

In contrast, we will not address the large body of studies that investigated the issue of time processing (for reviews see Buhusi and Meck, 2005; Eagleman, 2008; Grondin, 2010; Ivry and Schlerf, 2008). We will not review either those studies addressing time and space interactions from a psychophysical perspective (for an overview see Casasanto and Boroditsky, 2008).

Important pieces of evidence might be missing from the present review. However, the structure we propose here is intended to provide a first systematization of the various types of time–space interactions so far described and to better specify some important points under investigation, which in research papers are often overlooked.

1. The mental time line

We experience that time and space are tightly coupled every time we move from one place to another. This coupling is ubiquitous in several everyday contexts, including graphical representations which often resort, in Western cultures, to a left-to-right direction for indicating time flow (e.g., Fig. 1). Converging time–space interactions, found with various paradigms and in heterogeneous research domains, such as numerical cognition, visuospatial attention, response compatibility or embodied cognition, indeed suggest that humans do not process time and space separately but represent time as space. Indeed, several authors have recently referred to the possibility that humans represent time flow using a spatial layout, or a “mental time line” (Di Bono et al., 2012; Oliveri et al., in press; Ishihara et al., 2008; Magnani et al., 2011; Müller and Schwarz, 2008; Santiago et al., 2007, 2010; Vallesi et al., 2008, 2011; Weger and Pratt, 2008). The term mental time line (hereafter MTL; see Fig. 2) has been adopted in the literature as a catchy and immediate way to account for time–space interactions, but a coherent theoretical framework is still missing.

Here, on the basis of our systematic review of the literature on time–space interactions, later described in detail, we synthesize and extend the MTL hypothesis in terms of the following features:

(i) Time is represented along a spatial continuum akin to a line, where time flows from one extremity towards the other (e.g., past on one extremity and future on the opposite extremity). This applies both to time concepts (e.g. before–after) and temporal durations (e.g. brief–long).
(ii) The spatial orientation of the MTL is embodied and culturally mediated, because it follows the spontaneous scanning habits. If no particular manipulation is implemented it spontaneously conforms to writing direction and represents, in Western cultures, relative past on the left and relative future on the right.
(iii) Time is represented in terms of spatial position on the MTL not in absolute but in relative terms. That is, a given time quantity or time concept is not intrinsically left or right on the MTL but it is coded with respect to a reference point or interval.
(iv) Spatial attention is involved in accessing the MTL. Experimental manipulations of visuospatial attention, as well as impairments of spatial attention following brain damage, can affect time processing.

2. Time–space interactions

In this section we will review the heterogeneous evidence, so far largely unconnected, suggesting that time processing interacts with space processing by means of a mental time line.

2.1. Parallels with the mental number line

The vast majority of the effects found in the time domain show striking similarities with the interactions between space and numerical magnitude. Indeed the characteristics previously listed closely mirror those attributed to the mental representation for numbers, the so-called mental number line (see Hubbard et al.,

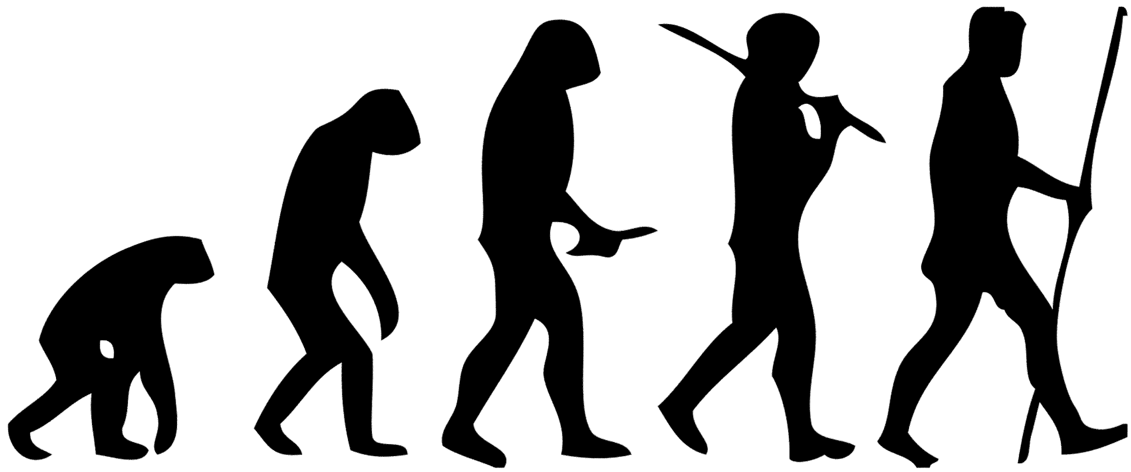

Fig. 1. A well-known graphic example of left-to-right representation of human evolution. Its popularity and effectiveness induces to think that it genuinely taps into a preferential way to spatially represent time flow from left to right. In addition, it has been suggested that rightward-oriented drawings of human profiles induce a sensation of being oriented towards the future (Van Sommers, 1984).

Source: http://en.wikipedia.org/wiki/File:Human_evolution_scheme.svg.

2005; Umiltà et al., 2009, for recent reviews; but see Fias et al., 2011 for a different account). The proposal that numbers are spatially represented finds its roots in the seminal study of Galton (1880), who found that some people report vivid introspective descriptions of numbers arranged into spatial forms (notably, spatial forms were also reported for temporal sequences such as months of the calendar year). A wealth of studies within the last two decades has established that the coupling between spatial and numerical processing is tight and systematic (for reviews see de Hevia et al., 2008; Hubbard et al., 2005; Umiltà et al., 2009). Indeed, the current leading view on the mental representation of numbers is that numerical magnitude is spatially represented on a mental number line (hereafter MNL), whereby the semantic value of a number would be indexed by its spatial position on the line. The MNL orientation is thought to follow writing direction and it would thus represent, in Western cultures, relatively small numbers on the left and relatively large numbers on the right (Dehaene et al., 1993; Zorzi et al., 2002). The numerical magnitudes on the mental number line are selected and activated by means of shifts of spatial attention, as corroborated by the finding that impairments/and or manipulations of attention result in biases within the numerical domain (Zorzi et al., 2002, 2012; Stoianov et al., 2008).

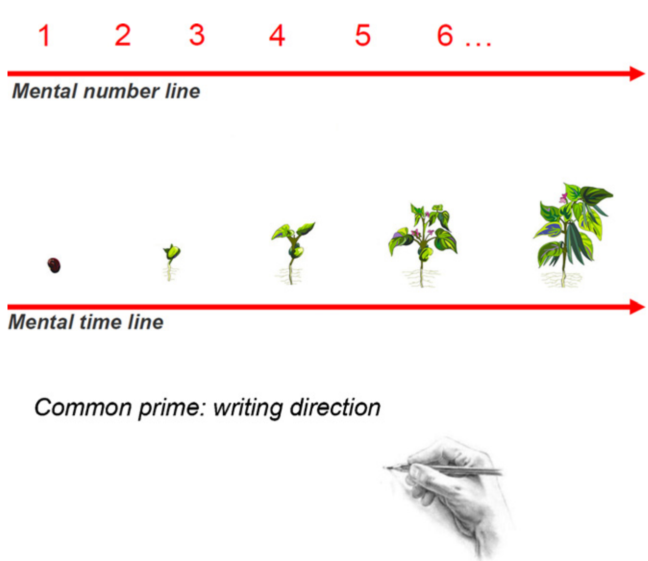

Fig. 2. A schematic representation of the mental number line and of the mental time line. The writing hand exemplifies the role of writing direction in the orientation of both mental lines.

Adapted from the images available at: http://poster.4teachers.org/worksheet/view.php?id=113333 and at: http://www.lefiabe.com.

Therefore, for every interaction examined, we first present the number–time interaction and then its homologue in the numerical domain. This comparison across domains should also allow us to anticipate trends (and avoid potential misunderstandings) which characterized the interactions with "space" within the better established numerical cognition domain and are being, or are likely to be, re-proposed within the time–space domain.

2.2. *Association with left–right responses*

2.2.1. *Left–short vs. right–long association*

Several studies described an association between temporal duration and spatial position of the effectors deputed to responding (short temporal durations associated with left space and long temporal durations associated with right space). An example of this interaction can be found in the duration judgement task used by Conson et al. (2008). Participants decided, by pressing two lateralized keys, whether the first or the second tone in a pair was shorter (or longer). Responses were faster when short and long durations had to be responded to with the left and the right effector, respectively. These spatial associations involve the relative left–right spatial position of the effectors rather than their absolute "leftness" or "rightness". Indeed, they are still present when responses are performed with crossed hands or with two fingers of the same hand (Vallesi et al., 2008, for time; Priftis et al., 2006, for number). Moreover, they extend to several others continuous quantities, such as physical size, luminance, and object size (Ren et al., 2011). The left–short vs. right–large association has been described to be influenced by repetitive Transcranial Magnetic Stimulation (rTMS) applied to the cerebellum (Oliveri et al., 2009a).

2.2.2. *Left–past vs. right–future association*

The association of "before" (past) with "left" and "after" (future) with "right" has also been described. In this case the spatial aspect is associated with a time concept that is independent from its duration, and thus cannot be considered an instance of the ubiquitous left–small vs. right–large association, as in the case of "left–short vs. right–long" associations. Studies showing this association thus support the possibility that time is represented according to a left-to-right mental line which cannot be merely considered an instance of the mental number line.

This association holds for letters of the alphabet, months of the year and days of the week (Gevers et al., 2003, 2004). These sequences (time ordered in the case of months and days) elicited an association with the spatial positions of the responses (i.e. *Monday* and *January* with the left; *Friday* and *December* with the right).

The same left–before right–after association can be found when the temporal onset of events is categorized. This association has been called "Spatial-Temporal Association of Response Codes" (STEARC) by Ishihara et al. (2008) who varied systematically the onset timing (early vs. late) of a brief probe stimulus following periodic auditory clicks. Participants had to press one of two lateralized response keys, depending on whether the onset of a given probe occurred earlier or later than expected, as compared to the previous clicks intervals. Again, left-sided responses to early onset timing were faster than those to late onset timing, whereas right-sided responses to late onsets were faster than those to early onsets.

This association can also be elicited by words and tenses (e.g. past vs. future) whose categorization as referring to the past or to the future is facilitated when the response mapping is congruent with the left–past right–future association (Torralbo et al. 2006; Santiago et al., 2007). Finally, the same association also holds when participants have to categorize the items of a story (presented as images) as preceding or following a reference item in the sequence, a finding which suggests that the association is not only found for overlearned sequences (Santiago et al., 2010).

Indeed, the left–before right–after association is not abolished when stimuli do not consist in a previously learned sequence but in a list of words without any temporal meaning and when temporal/ordinal aspects of elements to be responded to are irrelevant to the task (Previtali et al., 2010; see also Lakens et al., 2011; Van Dijck and Fias, 2011). When responses to non-temporal aspects of verbal stimuli have to be provided this interaction can disappear (Ulrich and Maienborn, 2010). Paradoxically, this finding renders even more striking the parallel with numerical cognition, where number–space interactions, besides being ubiquitous, are also very dependent on the relevance of the numerical information for the task and often require an explicit processing of the numerical magnitude to emerge (see later).

In the numerical domain, several studies have reported an association between numerical magnitude and spatial position of the response effector. This finding has been called Spatial Numerical Association of Response Codes (SNARC effect; Dehaene et al., 1993; Wood et al., 2008, for review) and constitutes, by far, the best known and most extensively investigated example of number–space interaction. The SNARC effect is usually investigated by means of parity judgment or magnitude comparison tasks performed in response to single digits presented at fixation. It consists of faster responses to relatively small numbers (e.g. 2) with the effector that operates in the left side of space and faster responses to relatively large numbers (e.g. 8) with the effector that operates in the right side of space. The SNARC effect indexes thus an interaction between side of response and numerical magnitude of the digit, which emerges even when number magnitude is task-irrelevant (like in parity judgement tasks). The effect is thought to arise because of a spatial correspondence, or lack of correspondence (i.e., corresponding vs. non-corresponding trials), between the position of the number on the MNL and the spatial position of the response (but see Proctor and Cho, 2006; Santens and Gevers, 2008; van Dijck et al., 2009).

2.3. Modulation by writing direction

We have already mentioned that the above described effect dissociates from the specific hand adopted because it is also found when responses are performed with crossed hands (Vallesi et al., 2008).

Several additional spatially characterized effects, reported in a number of heterogeneous domains, confirm that the preference for the left-to-right order is a consequence of the tendency to "align" events according to writing direction. For instance, in Western countries, the action agent is preferably represented on the left and the action object on the right (Chatterjee et al., 1999). This preference reverses in right-to-left readers (Maas and Russo, 2003) and follows the writing–reading direction not only for numbers (Dehaene et al., 1993; Shaki et al., 2009) but extends to the interaction with the processing of the spatial position of the stimuli (Zebian, 2005). Also, it exerts its influence on several other visuospatial tasks (Kazandjian and Chokron, 2008) including core processes such as the orienting of visuospatial attention (Spalek and Hammad, 2005). Crucially for our purposes, writing direction has been found to prompt also the direction of the spatio/temporal representations of sequential events (Fuhrman and Boroditsky, 2010; Ouellet et al., 2010b; Tversky et al., 1991). Ouellet et al. (2010b) asked Spanish and Hebrew speakers, differing in their reading/writing direction, to discriminate temporally characterized (past or future) auditorily presented words. Spanish participants showed, for past words, faster responses with the left effector, whereas for future words a right effector advantage emerged. Strikingly, Hebrew participants showed the reverse pattern, thus confirming a causal role of writing direction in determining the spatial representation of time. This preference can be reversed by presenting, to left-to-right readers, instructions written from right to left (Casasanto and Bottini, 2010, see also Ariel et al., 2011). It is somewhat paradoxical that the embodied or grounded cognition accounts, in spite of their emphasis on bodily motor mediated effects in cognition (see Barsalou, 2008, for review), did not highlight (see for instance Kranjec and Chatterjee, 2010) that motor-attentional habits might exert a major influence on the representation and processing of time. Two recent studies which examined the spatial characteristics of temporal representation in Mandarine speakers (Boroditsky et al., 2011; Miles et al., 2011) ascribed the finding of a vertical spatial layout for temporal representation to the presence of vertical metaphors for time in Mandarine language. The possibility that the factor leading the effect might have been, in fact, the participants' familiarity with up-to-down writing–reading direction was dismissed; (but see Boroditsky, 2011) as, a potential alternative explanation. In effect, we believe that the influence of writing direction upon temporal and numerical processing has so far provided the most convincing evidence supporting the view that visuomotor behaviour can deeply influence our cognitive representations of abstract concepts like time and number (see later discussion).

2.4. Nature or nurture?

It might be argued that the evidence reviewed so far ultimately demonstrates that the orientation of the spatial representation of time follows the writing direction. In fact, the picture is far more complex if we consider that linguistic factors (e.g., the different spatial metaphors for time), though we believe not predominant, might still play an important role in shaping time–space associations (Núñez and Sweetser, 2006; Boroditsky, 2011). Other cultural aspects also shape time representation as shown by Pormpuraaw, a remote Australian Aboriginal community where the spatial representation of time is absolute, that is related to the cardinal directions (Boroditsky and Gaby, 2010). Moreover, three lines of evidence, related to either temporal durations or numerical magnitudes, describe an association with space in contexts where the influence of cultural factors can be readily excluded.

First, 9-month-old infants seem to prefer the binding of stimuli with a long temporal duration with stimuli larger in size, more numerous or longer in length (Lourenco and Longo, 2010). Infants of the same age also consistently show overlapping representations for temporal duration and length (Srinivasan and Carey, 2010). According to these authors (p. 217) "functional overlap between representations of length and duration does not result from a metaphoric construction process mediated by learning to flexibly use words such as long and short. . . it may reflect an evolutionary recycling of spatial representations for more general purposes".

Second, several animal species (e.g., adult nutcrackers and newborn domestic chicks; Rugani et al., 2010, 2011) can present a surprising left-to-right preference for sequentially ordered items, which plausibly mirrors innate hemispheric asymmetries and not the presence of an oriented "mental line". As a consequence, to fully account for the spatial orientation of magnitude representations one should also consider the potential neurological constraints that might contribute to the tendency to render time and quantities spatial, as well as to order them from left to right.

Third, the direction and the amplitude of the SNARC effect was recently found to be influenced "on the spot" by different task demands, which interact with writing direction (Fischer et al., 2010; but see Treccani and Umiltà, 2011), thereby showing an unexpectedly high degree of plasticity. In sum, the coupling between magnitudes and space long before formal education, its extension to other animal species, and its cognitive flexibility in human adults clearly show that writing direction is a very reliable prime for the direction of these temporal/numerical lines but it cannot be considered the only factor influencing the way time/numbers are associated with space.

2.5. Interaction with the spatial position of the stimulus

The spatial position of a stimulus influences its perceived duration. The duration of stimuli presented in the left hemispace is underestimated, as opposed to the duration of stimuli presented in the right hemispace which tends to be overestimated (Vicario et al., 2008). The perceived temporal duration of visual stimuli can be also biased according to the left vs. right spatial position of auditory distracters (see also Vicario et al., 2009, for a study with a more stringent counterbalancing of response mappings). Crucially, the interaction with spatial position is also found with time concepts, conveyed by words and verbs (e.g., past vs. future: "yesterday" vs. "tomorrow" or "he said" vs. "he will say", Santiago et al., 2007; see also Torralbo et al., 2006). Indeed, temporally characterized words, when presented in the right hemispace, showed a stronger association for future with respect to past. An interaction between spatial position and temporal meaning of a verb was also found by Ouellet et al. (2010a) in a study where the different tenses (e.g., "he said" vs. "he will say") biased the processing of targets presented at locations consistent with a left (past) to right (future) mental representation of time. A left vs. right bimanual response was required with a fixed mapping for every participant, who had to perform tasks which were orthogonal to the time information, such as pressing a key corresponding to the spatial position of a lateralized target (Experiment 1) or corresponding to the spatial orientation of an arrow (Experiments 2 and 3). Time–space interactions thus seem to emerge when a temporal task is characterized by a spatial aspect, independently of whether it manifests itself in the form of lateralized response keys or in the form of a spatial lateralization of the target. This effect of stimulus position has again a parallel in the number domain, in terms of interaction with numerical magnitude.

Two seminal studies assessing the way lateralized digits are processed are those from Tlauka (2002) and Mapelli et al. (2003). We will focus on the latter. Mapelli and colleagues were particularly interested in the interaction of the SNARC with the Simon effect. The Simon effect refers to the tendency to respond faster and more accurately when the spatial position of the target (which is irrelevant to the task) is spatially corresponding with the position of the response (Simon and Rudell, 1967). Mapelli and colleagues found both SNARC and Simon effects but no interaction, and concluded that the SNARC is not just a particular form of Simon effect. Further studies, however, showed that, under specific conditions, the SNARC and the Simon effects interact (e.g. Notebaert et al., 2006).

2.6. Shifts of attention

A key role in mediating spatio–temporal interactions seems to be played by spatial attention. Spatial attention allows one to identify locations relevant for behaviour, and enhances the efficiency of the processing at the selected spatial location.

Spatial attention modulates performance in detection tasks that require unimanual responses, where past-related words induce a leftward orienting of attention whereas future-related words induce a rightward orienting (Weger and Pratt, 2008, Experiment 2B). These authors are, however, very cautious in interpreting their results as consequential of a pure orienting of attention and maintain that "the fact that the pattern is substantially weakened in a detection task indicates that the effect is primarily – although not necessarily *exclusively* – due to a facilitation of response codes, rather than to an impact on stimulus processing" (p. 429). A similar finding has been described also in right hemisphere damaged patients, a clinical population characterized for deficits of visuospatial orienting in the contralesional space (Pun et al., 2010; later described more in detail) suggesting that the effect is truly attentional. The differences between experiments investigating pure attentional processes and experiments investigating effects more similar to response compatibility are not always straightforward. For instance Ouellet et al. (2010a) investigated the performance of healthy participants following central presentation of spatially characterized words. Their experiments, however, although somehow similar to those of Weger and Pratt (2008), required a response to a spatial aspect of the stimulus, not a mere detection response. Thus, the facilitation they found (e.g., left–before and right–after) should not be taken as evidence of a pure attentional orienting but instead ascribed to an interaction with the spatial position of stimulus/response (as reported in the studies previously reviewed). Further empirical evidence is thus needed to make more solid the possibility that the processing of temporal concepts necessarily gives rise to shifts of visuospatial attention.

Within the numerical domain the mediating role of spatial attention is well established. Indeed, spatial attention is thought to be the mechanism that allows movements along the spatially organized MNL [Knops et al., 2009; Zorzi et al., 2012; Hubbard et al., 2005; Umiltà et al., 2009; see Gevers et al., 2010, for a dual-code (spatial and verbal) hypothesis]. It has indeed been proposed a direct link between the processing of numerical magnitude and orienting of visuospatial attention. Fischer et al. (2003) reported faster detection of right visual targets when they were preceded by a large with respect to a small central digit, whereas the opposite was found for left visual targets. It is still unclear whether these effects properly fulfil criteria for automaticity of attention orienting (e.g. Bonato et al., 2009; Galfano et al., 2006; Ranzini et al., 2009; Ristic and Kingstone, 2006) and whether shifts in spatial attention precede (causal role hypothesis) or follow (epiphenomenal hypothesis) the processing of numerical magnitudes. The processing of numbers, however, results in a reliable orienting of spatial attention when numerical magnitude is relevant for the task at hand (e.g., Casarotti et al., 2007).

The neural circuitry subtending these effects is thought to be the one subtending the orienting of visuospatial attention (see Casarotti et al., 2012), which includes the human homologues of the Ventral intraparietal (VIP) and Lateral intraparietal (LIP) areas. It has been proposed that this visuospatial circuitry is partially recycled for the manipulation of numerical magnitudes (Dehaene, 2009; Hubbard et al., 2005).

2.7. Visuospatial priming

A lateralized visual distracter can interfere with the processing of durations. Responses to auditory temporal durations (short vs. long) can be influenced by task-irrelevant visuospatial cues, with leftward cues inducing an underestimation of temporal duration and rightward cues inducing overestimation (Di Bono et al., 2012). Importantly, responses were provided verbally and they were not spatially characterized, thereby ruling out the possibility that the effect is located at the response selection stage.

Earlier studies investigated the effect of task-irrelevant lateralized visual cues in the numerical domain. Stoianov et al. (2008; also see Kramer et al., 2011) showed that vocal, non-spatial responses to the parity or magnitude of centrally presented digits is influenced by the irrelevant spatial cue flashed shortly after the target digit. Task-irrelevant lateralized primes can also modulate numerical interval bisection (Nicholls and McIlroy, 2010), a task that has provided key information about the disruption of number processing in right hemisphere damaged patients with disorders of visuospatial processing (see later discussion).

2.8. Effect of biases of spatial attention (right hemisphere damage (RHD)/neglect, prismatic adaptation (PA), optokinetic stimulation (OKS))

2.8.1. RHD/neglect

A spatially characterized bias affecting time processing has been observed in right hemisphere damaged (RHD) patients. In some, albeit not in all, studies the RHD patients presented with left spatial neglect, a syndrome characterized by the failure to orient towards the space (including representational space) opposite to the lesioned hemisphere (i.e. contralesional). These patients show a significant temporal underestimation in a time bisection task, as compared with RBD patients without neglect (Oliveri et al., in press, 2009b). In other words, RHD patients with neglect present a contralesional bias in visuospatial attention that seems to extend to the time domain, in the form of an underestimation of temporal durations (but see Calabria et al., 2011, for a partially different account).

RHD patients without evidence of neglect on paper and pencil tasks were found to be particularly slow when they had to detect contralesional targets if their spatial attention was engaged by (rightward orienting) future-related centrally presented words (Pun et al., 2010). Also this finding supports a key role of spatial attention in temporal processing: indeed, it closely resembles the disengage deficit usually found in RHD patients, consisting in particularly slow and error-prone detection of left visual targets when attention had been previously cued by a centrally presented rightward-oriented arrow (e.g. Bonato et al., 2009). The presence of a temporal bias in patients without neglect is less surprising than it might appear at first sight, because standard paper and pencil testing are rather insensitive in detecting the presence of neglect (as opposed to computer-based testing, see Bonato et al., 2010, 2012a, in press; Bonato, 2012 for review). Although less likely, a deficit that is confined to the representational domain is also possible (see Pun et al., 2010).

Within the numerical domain, studies on RHD patients with left neglect have provided crucial evidence supporting a key role for spatial attention in accessing numerical magnitude upon the MNL (see Umiltà et al., 2009 vs. Fias et al., 2011, see also Doricchi et al., 2005).

When asked to verbally bisect a numerical interval (e.g. what number is halfway between “2” and “6”) patients with left neglect systematically misplace the midpoint of the numerical interval (e.g., responding “5” instead of “4”) and their errors closely resemble the typical pattern found in the bisection of visual lines: that is, increased rightward shifts with increasing line length and a reverse leftward bias (crossover effect) with very short lines (Zorzi et al., 2002). This bias does not seem to be directly related to neglect severity in peripersonal space (Doricchi et al., 2005; Priftis et al., 2006; Rossetti et al., 2004) nor in the O'Clock Test (Rossetti et al., 2011). However, this peculiar form of representational neglect suggests that the MNL is more than a mere metaphor and that numbers might be represented in a way that is truly spatial in nature (Zorzi et al., 2012).

2.8.2. Prismatic adaptation and optokinetic stimulation in healthy participants

Perceived temporal durations can be affected by manipulations of visuospatial attention implemented through prismatic adaptation (PA; Frassinetti et al., 2009). In the PA technique, participants are asked to perform reaching tasks while wearing deviating (leftwards or rightwards) prisms (goggles). Once participants are adapted to the effects of the prisms these are taken off and participants are asked to perform again the reaching tasks. Participants then show, in their reaching performance, a compensatory after-effect in the form of a spatial deviation in a direction opposite to the “illusionary shift” induced by the prisms. Prisms inducing a leftward after-effect result in an underestimation of time duration in both a reproduction and in a bisection task in healthy participants, presented with visual stimuli of different durations. In contrast overestimation emerges following adaptation to prisms inducing a rightward after-effect (Frassinetti et al., 2009). The processing of temporal duration is also influenced by another technique that can bias visuospatial attention, that is optokinetic stimulation (OKS; Vicario et al., 2007). Consistently with the direction of the attentional imbalance induced, leftward OKS reduces the perceived temporal duration of visual stimuli, whereas the opposite holds for rightward OKS (Vicario et al., 2007). Loftus et al. (2008) showed that also in the numerical bisection task performance can be spatially biased by PA. They showed that the “normal” leftward bias presented by healthy participants was corrected by a short period of visuomotor adaptation to prisms with a rightward after-effect. Alternative techniques biasing visuospatial attention, as motion adaptation or random dot kinematograms, also exert an influence on numerical magnitude processing (Renzi et al., 2011). Finally, Nicholls et al. (2008) found that PA also affects the representation of the letters of the alphabet, as if the latter would be spatially characterized.

2.8.3. PA and OKS in RHD/neglect

PA and OKS are effective not only in modulating visuospatial attention of healthy participants but are also effective in modulating the visuospatial bias of RHD/neglect patients.

With respect to the time domain, two recent studies (Magnani et al., 2011; Oliveri et al., in press) showed that RHD patients present, in temporal bisection tasks, an underestimation of temporal durations, which parallels their contralesional deficits in spatial-representational hemispace and that this bias can be affected by PA. The overall performance suggests that the task was overall difficult to be performed accurately by the patients, but the modulation induced by PA demonstrates a key role of spatial attention in producing the effect and parcels out several “non-attentional” explanations.

In Magnani et al. (2011) RHD patients without neglect presented with a tendency to underestimate temporal durations in a time reproduction task. PA inducing leftward after-effect increased temporal underestimation in RHD patients and controls (as in Frassinetti et al., 2009), whereas it was ineffective in left brain damaged patients. In contrast, PA inducing a rightward after-effect failed to affect time perception in either group. Crucially, however, in a time bisection task neglect patients showed a particularly severe temporal underestimation bias (Oliveri et al., in press), as if they were neglecting the "leftmost" part of their mental time line (MTL), in close parallel with the findings in the numerical domain (Zorzi et al., 2002). The same group of neglect patients also showed a reduction (in contrast to the increase shown by the RHD patients of the study previously described) of their underestimation following PA generating a leftward after-effect, thereby showing that temporal deficits in neglect closely relate to attentional/spatial impairments, and also confirming that these can be reduced by a re-balance of visuospatial attention. Both RHD patients without neglect and healthy controls showed temporal underestimation following PA inducing a leftward after-effect, again suggesting that spatial attention plays a key role in the time domain.

In the numerical domain, both PA (Rossetti et al., 2004) and OKS (Priftis et al., 2012) have been shown to modulate the number bisection bias characterizing neglect patients.

An OKS-like manipulation has been also shown to modulate the response slowing typically found in left neglect patients performing magnitude comparison tasks for digits immediately smaller than the reference number (Vuilleumier et al., 2004). In a study by Salillas et al. (2009) a cloud of dots moving leftwards reduced this characteristic slowing.

In summary, PA, OKS and RHD are three conditions in which a bias in visuospatial attention, either due to an experimental manipulation or to the presence of a neuropsychological disorder, affects both temporal and numerical processing, thereby supporting our contention that time and numbers are spatially represented. The modulation induced by PA in time processing in RHD patients with neglect, although so far limited to brief durations, allows one to exclude that the bias that these patients present in time processing might be due to factors other than the bias in visuospatial attention (Bonato et al., 2012b).

2.8.4. Interactions with body movements in space

The present category encompasses the general issue of interactions between a movement in the physical space and time processing, beyond the association with writing direction already described.

In some cultures, there is a tendency to gesture from left to right when describing events unfolding in time as well as a peculiar past-far present-close tendency in gestures (Núñez and Sweetser, 2006). Moreover, the spontaneous fluctuations in the individual postural sway while mental time travel is performed show that mental time travel has an observable behavioural correlate – the direction of people's movements through space (i.e., retrospective thought = backward movement, prospective thought = forward movement; Miles et al., 2010). These movements are considered to be overt behavioural markers of the otherwise invisible mental operation of association of time with space (Miles et al., 2010).

Also bodily mediated space–number interactions are rather striking. For instance, in a random number generation task, the frequency with which digits are generated is modulated by the bodily spatial position (Loetscher et al., 2008). In this study, a rightward head turn induced a more frequent generation of large digits, whereas small digits were more frequently generated following a leftward head turn. Another prominent example involves eye movements; indeed the lateral position of the eyes (leftwards/rightwards) during random number generation can predict the magnitude of the number (smaller vs. larger) a participant is about to produce (Loetscher et al., 2010). Moreover, performing additions and subtractions involves a network that is partially overlapping with the network active when performing lateral eye movements, with cortical activations during addition vs. subtraction being similar to those for performing rightward vs. leftward eye movements, respectively (Knops et al., 2009). These results fit well with the premotor theory of spatial attention (Rizzolatti et al., 1987; see Casarotti et al., 2012, for a computational model), which maintains that attentional shifts recruit the neural circuitry devoted to saccadic programming, as if attentional shifts were saccades not performed.

Finally, numerical magnitude can also interact with complex movements and speed up the initiation time of grip opening (large magnitudes) or closing (small magnitudes; Andres et al., 2004).

2.8.5. The ordinality issue

There are few studies addressing ordinality as a common characteristic belonging to both temporal sequences and numerical quantities. This issue is important for our purposes because one could claim that number and time are both ordered "sequences" and thus the commonalities between the two domains might be due to this characteristic (see Tzelgov and Ganor-Stern, 2005). The issue is in fact controversial, because some studies (e.g. Turconi et al., 2006; Turconi and Seron, 2002) argued for largely (though not fully) independent processing of order and numerical magnitude.

For example, Turconi and Seron (2002; see also Delazer and Butterworth, 1997) described a patient who could perform a standard number comparison task (which number is larger?) but had severe problems in a numerical order task (which number comes first?). Moreover, non-temporal ordered information (e.g. letters of the alphabet) does not seem to consistently trigger shifts of spatial attention (Casarotti et al., 2007; but see Nicholls et al., 2008), or interactions with the perceived temporal duration (Oliveri et al., 2008), thus questioning whether order makes numbers and temporal sequences equal. Dehaene (2009) suggested that number representation should be considered to rely on a largely independent network, highlighting that, according to his view, numbers are not merely encoded in terms of order. The similarity can also be attributed to a developmental process that bootstraps the representation of non-numerical order from the child's numerical representation (see Berteletti et al., 2012, for a developmental study on the representation of ordered sequences).

A recent fMRI study (Zorzi et al., 2010) investigating brain areas devoted to the processing of numbers and ordered sequences showed that intraparietal areas apparently presenting overlapping activations for numbers and ordered sequences (Fias et al., 2007) can in fact be resolved into separate networks by more sophisticated analyses with multivariate classifiers. Nonetheless, the relation between the mechanisms underlying cardinality and serial order processing needs to be further investigated and seems to be far from being understood (Nieder, 2005).

2.9. Interim summary

The systematic parallel between time–space interactions and number–space interactions is summarized in Table 1. Four phenomena are particularly important in supporting a representation of time with spatial characteristics:

(i) responses performed in the relative left space are associated with "before" and "past" stimuli, whereas responses performed in the relative right space are associated with "after" and "future" stimuli. Remarkably, this association is related to the direction of writing and reading (Ouellet et al., 2010b);

Table 1
A synopsis of the interactions with spatial aspects found in numerical and time domains. The two columns for time refers to studies where the time aspect was "before–after" vs. those where a temporal duration was investigated. One/two relevant studies are cited for each effect. The rightmost column reports whether the effect should be considered as evidence for a representation that is spatial in nature.

Effect	Numerical domain	Time domain (before–after)	Time domain (duration)	Evidence for a spatial representation?
Association with left–right responses	SNARC Dehaene et al. (1993)	STEARC Ishihiara et al. (2008); Gevers et al. (2003)	Vallesi et al. (2008)	Debated
Shifts of attention	Fischer et al. (2003)	Weger and Pratt (2008)		Yes
Modulation by writing direction	Dehaene et al. (1993)	Tversky et al. (1991)		Not necessarily
Interaction with the spatial position of the stimulus	Tlauka (2002) Mapelli et al. (2003)	Santiago et al. (2007)	Vicario et al. (2008, 2009)	Yes
Visuospatial priming	Stoianov et al. (2008)		Di Bono et al. (2012)	Yes
Right brain damage/hemispatial neglect	Zorzi et al. (2002)	Pun et al. (2010)	Oliveri et al. (2009b)*	Yes
Prismatic adaptation/OKS in healthy participants	Nicholls et al. (2008)		Vicario et al. (2007) Frassinetti et al. (2009)*	Yes
Prismatic adaptation/OKS in neglect patients	Rossetti et al. (2004) Salillas et al. (2009)		Oliveri et al. (in press)*	Yes
Distance effect	Moyer and Landauer (1967)	Santiago et al. (2010)		No
Interaction with physical size	Besner and Coltheart (1979)		Xuan et al. (2007)	No
Spatial forms synaesthesia	Galton (1880)	Seymour (1980)		Debated
Logaritmic compression	Shepard et al. (1975)	Arzy et al. (2009a)		No
Interactions with body movements in space	Andres et al. (2004); Loetscher et al. (2008)	Núñez and Sweetser (2006)		Yes

* Bisection and/or reproduction tasks, where a before/after judgement may also have been employed.

(ii) these associations are found also when time/sequential information is task-irrelevant (Previtali et al., 2010);
(iii) the processing of time-related information evokes shifts of spatial attention, and it interacts with the spatial position of the stimuli (Weger and Pratt, 2008);
(iv) RHD patients show a visuospatial deficit when processing time information (Pun et al., 2010).

The list above can be amended with four additional phenomena regarding the processing of brief temporal durations:

(v) time perception can be modulated by PA and OKS (Frassinetti et al., 2009; Vicario et al., 2007);
(vi) the bias of RHD patients can be modulated by PA (Oliveri et al., in press);
(vii) relative rather than the absolute spatial position of the effectors determines the time–space associations (Vallesi et al., 2008);
(viii) The spatial position of a task-irrelevant lateralized visual cue affects the judgement of durations (Di Bono et al., 2012).

3. Further characterization of time–space interactions

3.1. Short/left and long/right vs. before/left and after/right associations

As noted before, the evidence in favour of a left-to-right representation of time, which emerges from studies associating short with left and long with right responses, is not particularly compelling. Indeed, in this case, the short–left long–right association might be seen as a particular case of the SNARC effect. We maintain that the existence of a MTL requires evidence of interactions with a temporal dimension involving before–after concepts and not merely short–long concepts. This kind of evidence can be primarily found in those studies that show an association between past-related concepts (or items presented before a reference) and left space along with an association between future-related concepts (or items presented after a reference) and right space, as for instance shown by Santiago et al. (2007, 2010), Previtali et al. (2010), Lakens et al. (2011), and Weger and Pratt (2008). In our view, these studies provide the clearest evidence for a representation that is spatial in nature and which specifically characterizes time concepts. In contrast, the studies showing an association with short–long durations equally support the possibility that a common system would subtend the processing of all magnitudes (e.g., Walsh, 2003; see later discussion). This distinction, however, is not always clear-cut. There are several studies, "intermediate" between the two categories, where the temporal task is characterized, by both the "brief–long" and the "before–after" dimensions, (e.g. time bisection and reproduction studies; Frassinetti et al., 2009; Grassi and Bonato, 2012; Oliveri et al., in press).

3.2. Affordances and abstract concepts; metaphoric structuring and embodied cognition

According to Boroditsky (2000, 2001), spatial metaphors for time in language index the way time is merged with space by our cognitive system. However, spatial metaphors for time in Western cultures are mainly related to the back-forth axis rather than to the left–right axis (Radden, 2004). Thus, the intriguing hypothesis that the spatial representation of time might be causally linked to linguistic metaphors for temporal flow can account for some results (e.g. Miles et al., 2010) but falls short in explaining the mounting evidence that the spatial coding of time follows writing direction (Fuhrman and Boroditsky, 2010; Ouellet et al., 2010b; Tversky et al., 1991).

The broad idea that some abstract concepts are represented in terms of more concrete, spatial domains (Casasanto and Boroditsky, 2008; Lakoff and Johnson, 1999; Tversky, 2000) seems to be, in contrast, more tenable, and the tendency to translate concepts from abstract to non-abstract (spatially characterized) domains seems to be ubiquitous. Associations between space and objects or concepts have been described for a wide variety of paradigms and contexts, including abstract entities (Chasteen et al., 2010), spatially oriented objects (Estes et al., 2008), adjectives (Meier and Robinson, 2004), and pitch height (Rusconi et al., 2006). The complexity of these interactions is confirmed by the finding that the semantics of particular locative prepositions constrain temporal concepts paired with them (Kranjec et al., 2010).

The mental representations of (abstract) things that cannot be seen or touched may be based, at least in part, on representations of physical experiences in perception and motor action (see Casasanto and Boroditsky, 2008; Barsalou, 2008 for review). It is then possible that temporal concepts are embodied. Roughly speaking, a concept is embodied when it is cognitively implemented as *mental simulation* and, as a consequence, it is supposed to interact with sensorimotor transformations and movement planning. The previously mentioned studies by Miles et al. (2010) and by Núñez and Sweetser (2006) are rather striking examples of embodiment in time processing. These findings again parallel the numerical domain, where effects of numerical magnitudes on affordances have been documented (Badets et al., 2007). We reiterate that one crucial (though overlooked) embodied aspect of time-space interactions derives from writing direction, which primes the direction of these associations (Boroditsky et al., 2011; Ouellet et al., 2010b; Tversky et al., 1991; Miles et al., 2011). Also mental arithmetic can be spatially biased, as shown by the effect called Operational Momentum (McCrink et al., 2007; see also Knops et al., 2009). The Operational Momentum consists in the tendency to produce responses larger than the correct ones when performing additions and responses smaller than the correct ones when performing subtractions. No corresponding effect has been so far described in the time domain.

3.3. Perisaccadic distortions in time–space

Important suggestions on the tight link between time and space come from the specific research domain of perisaccadic perceptual distortions (Yarrow et al., 2001; Morrone et al., 2005). The compression effect, which takes place for both space and time in a temporal window occurring around the execution of a saccade, has been recently shown to extend to non-symbolic numerical information (Burr et al., 2010). It thereby constitutes one of the few examples where the time–space interaction was investigated before the number–space one.

This research domain has been extended to show that attention can alter the perceived temporal duration while time intervals presented at different spatial locations are processed (Cicchini and Morrone, 2009). It also includes the concept of motion, i.e. the condition where time and space by definition interact in the physical world (see Morrone et al., 2010, for review).

3.4. Distance effect

One of the most relevant, stable and informative findings in numerical cognition is the distance effect, which indexes progressively slower and more error-prone responses as the numerical difference between two numbers decreases (Moyer and Landauer, 1967). The distance effect is not exclusive to numbers but it has been described for a variety of perceptual/cognitive domains, including time.

In Santiago et al. (2010), a categorization was required in the temporal order of appearance of centrally presented sequential items of a story with respect to a reference image. Results showed a distance effect between the reference and the target. It is worth noting that the distance effect is not evidence for a representation that is spatial in nature. The distance effect extends to all physical magnitudes and even to semantic relations. It would seem highly implausible to postulate the existence of a spatial representation of object concepts to explain, for instance, that a hammer is "closer" to a nail than to a tree. Accordingly, the distance effect in the number domain is thought to reflect the analogical nature of magnitude representations (Zorzi et al., 2005; Stoianov and Zorzi, 2012) but it is orthogonal to the issue of whether the representation is truly spatial in nature.

3.5. Logarithmic compression

Arzy et al. (2009a) showed that "self-projection" in time depends logarithmically on the temporal distance between the imagined "location" on the MTL and the "location" of another imagined event. The authors interpreted this pattern of results as suggestive that the MTL might be spatially characterized.

Also the mental number line is thought to be logarithmically compressed (Dehaene, 2003; Shepard et al., 1975), in analogy with the representation of physical quantities. Though logarithmic compression is often described in terms of decreasing "distance" between items as a function of increasing magnitude (e.g., Dehaene, 2003), compressive effects are usually not considered to be evidence for a spatial representation (as happens for the distance effect, see above).

4. Some dissociations

There is consistent evidence that the overlap between temporal, numerical, ordered and quantity-related information is not ubiquitous and that important dissociations can be found between these domains (e.g. Agrillo et al., 2010; Cappelletti et al., 2009, 2011a,b, submitted for publication; Castelli et al., 2006; Dormal et al., 2008; Roitman et al., 2007; Zorzi et al., 2006). For instance, temporal discrimination is spared in adults with developmental dyscalculia (Cappelletti et al., 2011b). Impaired number processing in developmental dyscalculia is, then, unlikely to originate from systems initially dedicated to continuous quantity processing of which time could be considered an example. These data thus reinforce the idea of a quantity system shared only in part across numerical and temporal dimensions. Similar findings, supporting the hypothesis of partially separated networks, were obtained from an fMRI study (Cappelletti et al., submitted for publication). Despite the studies describing general deficits for time processing in RHD patients (Basso et al., 1996; Danckert et al., 2007), it is still unclear whether distortions of time representation in neglect parallel the patients' visuospatial bias. There is initial evidence that this might be the case (Pun et al., 2010), a possibility confirmed by the modulation of the time bias elicited through OKS or PA. The performance of neglect patients (Umiltà et al., 2009) has also highlighted a specific status for numerical information. For instance, bisection tasks for overlearned time ordered sequences, such as the months of the year, showed a different representational bias with respect to numbers (Zorzi et al., 2006). Studies on neglect patients might provide an important contribution to clarify the complex boundaries between the spatial characteristics of number and time processing.

5. Open issues

One first, important caveat in the discussion of time–space interaction is that very different time scales, from less than a second to several years, are lumped together when heterogeneous studies are considered. The same mechanism is unlikely to be responsible for our ability to process enormously different time intervals as well as to account for past and future thinking. For instance, a key distinction that is made in the "classic" temporal processing literature is between the processing of supra- and sub-second temporal intervals. Grondin (2010) suggested that the differences between sub- and supra- second intervals might be due to the implementation of segmentation processes for the longer (but not the shorter) intervals. In the absence of specific monitoring strategies, participants might, for instance, spontaneously implement counting procedures, which allows one to perform an easier quantification of temporal lengths but also renders critical the interpretation of the potential interactions found with respect to numerical processing.

Moreover, it should be noted that studies investigating sub- and supra-second intervals typically adopt very different methodologies and that the previously reviewed task requiring the processing of a temporal duration typically adopt brief stimuli (e.g. below 2 s). What is tenable, however, is that, independently of the heterogeneous cognitive processes involved, time concepts and duration processing converge in left-to-right associations with space.

Another important aspect of time–space–quantity interactions is that they emerge also cross-modally (e.g. between temporal meaning, space and loudness). In the study of Lakens et al. (2011), future-related words auditorily presented in the right channel were perceived to be louder than past-related words. Other kinds of cross-domain interactions (e.g. temporo-tactile) have also been described (Occelli et al., 2011, for review).

5.1. The polarity correspondence theory

We were rather detailed in describing, for several of the reviewed studies, the modality of response mapping. This was done because several studies adopted lateralized responses and, quite frequently, focused on the interaction between stimulus temporal characterization/duration and spatial position of the responses (e.g. Gevers et al., 2003, 2004; Vallesi et al., 2008).

The advantage found for the (compatible) mapping left-“short/before” and right- “long/after” vs. the (incompatible) mapping left “long/after” and right “short/before” cannot be, however, unequivocally attributed to a representation with spatial characteristics. Indeed, it can alternatively be ascribed to a general tendency to polarize, in tasks where binary responses are required, both the characteristics of stimuli and of responses. The influential “Polarity Correspondence Principle” of Proctor and Cho (2006) posits that, when a “structural” polarization of a stimulus (e.g. small–big) overlaps with response polarization (e.g. left negative–right positive), a facilitation in response selection occurs, whereas responses are slower and more error-prone when this overlap does not occur. Thereby the Polarity Correspondence Principle accounts for results of studies comparing different mappings for a large number of paradigms according to a “structural” overlap, and not according to the presence of a mental representation with spatial characteristics.

This criticism has been levelled, within the numerical domain, in particular at the explanation of the SNARC effect, which, according to some (Proctor and Cho, 2006; Santens and Gevers, 2008) should not be considered evidence for a spatial layout of numerical representations. The same criticism can plausibly be directed also to paradigms adopting binary responses for time intervals and durations. Although the Proctor and Cho (2006) criticism might be applied to several studies it cannot easily account for the results of those studies not adopting bimanual responses (Pun et al., 2010; Weger and Pratt, 2008, Experiment 2B; Di Bono et al., 2012) or in which the temporal aspect was irrelevant to the task (Gevers et al., 2003; Ouellet et al., 2010a; Previtali et al., 2010).

In addition, there are also studies (e.g. Vicario et al., 2007) which, although making use of lateralized responses, merged together the two mappings and avoided any comparison between mappings. Furthermore, the polarity correspondence theory cannot easily account for the results of studies of culturally mediated preference which avoid binary responses. For instance, the spatial layout spontaneously created to represent an action being performed from an active agent follows the direction of writing (Maas and Russo, 2003). Also, the reversal of magnitude-related attentional effects when a right-to-left representation is evoked is not easily explained by the polarity correspondence theory (but see Proctor and Cho for an interpretation of the reversed number–space association

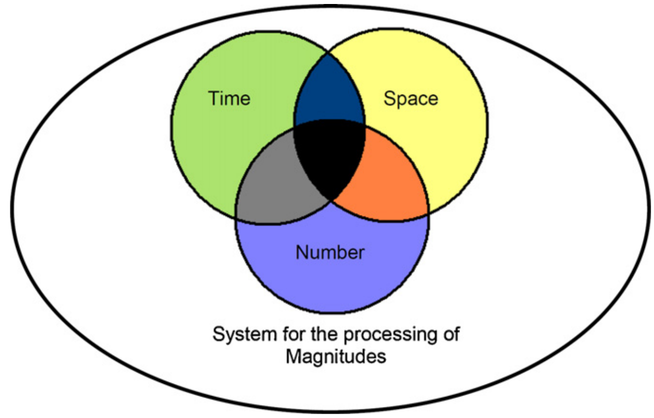

Fig. 3. A schematic representation of the ATOM theory.
Adapted from Walsh (2003).

described by Bächtold et al., 1998). Finally, the finding that the SNARC effect can be modulated by the direction of reading performed immediately before a numerical task (Fischer et al., 2010) questions the explanation related to the polarity correspondence account, which posits a stable conceptual marking of concepts as positive or negative. In summary, although the Polarity Correspondence Principle can constitute an alternative explanation for the results of some studies, several lines of research show that a polarity correspondence is only part of more complex picture, and in several studies this criticism cannot be applied. Consequently, it cannot be invoked to generally dismiss the possibility that time and space processing genuinely interact. However, it can provide a parsimonious explanation of the results for some specific studies, in which no counter-solutions to this potential confound have been implemented.

6. An alternative hypothesis: a common system for magnitude processing

A second group of studies, reporting interactions between numbers and space, time and space, or even time and number, calls for an explanation in terms of a common system for magnitude processing, as in the A Theory Of Magnitude (ATOM) proposal (Walsh, 2003; Bueti and Walsh, 2009, see Fig. 3), rather than a MTL.

The ATOM hypothesis does not maintain a spatial representation for time but, more generally, a common system for magnitude processing, including space, time, and numbers. Space and time are seen as “coupled metrics for action” and the place for this coupling is identified in the parietal cortex. The proposal of Bueti and Walsh (2009) is that humans learn about space/time associations while planning and performing actions. The system for number processing would then develop, phylogenetically later on, based on this system. In other words, the same brain areas and cognitive mechanisms for spatio–temporal transformations for action would be co-opted for developing a system devoted to number processing. The parietal lobes would be equipped with “an analogue system for action that computes ‘more than–less than’, ‘faster–slower’, ‘nearer–farther’, ‘bigger–smaller’, and it is on these abilities that discrete numerical abilities hitched an evolutionary ride” (Bueti and Walsh, 2009, p. 1832).

The hypothesis of a common system for processing numerical and non-numerical quantities is supported by several studies (e.g. Cantlon et al., 2009, for review; Cohen Kadosh et al., 2008; but see Castelli et al., 2006, for a different view). In addition to behavioural data, the evidence for a common processing mechanism is inferred from the overlap of neural structures devoted to visuospatial processing and to time representation (Danckert et al., 2007; Bueti et al., 2008a). Walsh (2003) carefully avoids any "attentional" explanation for the various interactions (indeed, he argues that attention has been too frequently evoked post hoc to explain opposite findings). Space might be the common metric for representing abstract, non-spatial entities, such as time, because space is rooted in the cortical networks that perform basic sensorimotor transformations (Bueti et al., 2008b). However, Walsh (2003) and Bueti and Walsh (2009) point out that sensorimotor integration occurs for both space and time, thereby avoiding to attribute to the spatial aspect the pivotal role which instead characterizes the MTL.

Stroop-like effects (see below) strongly support the existence of a common system for the processing of magnitudes, as proposed in ATOM. There is empirical support for the possibility of motor-related interactions between systems devoted to magnitude processing (Chiou et al., 2009; but see Fischer and Miller, 2008). In the former study, a compatibility effect between the numerical magnitude of a digit and the appropriate action (pinch vs. clutch) required to grasp the object coupled with the digit emerged in both manual and vocal responses. In contrast, such compatibility effect was absent when the parity judgment was coupled with colour-related or perceptual size. At the same time, however, there is also evidence that these interactions might be unidirectional and not bidirectional. Casasanto and Boroditsky (2008, p. 579) comment that: "people are unable to ignore irrelevant spatial information when making judgments about duration, but not the converse".

According to classical models, organisms could quantify time and number simultaneously by using multiple switches and accumulators and the information about different magnitudes may hence be analysed separately and compared (or integrated) according to metrics unique to each comparison (Meck and Church, 1983). Thus, it is highly plausible to envisage a single, although distributed, system for quantity processing. As stated by Buhusi and Meck (2005, p. 755) "time might be represented in a distributed manner in the brain . . ." and (p. 763) "As these areas are involved in several cognitive phenomena, it is likely that this circuit is not limited to temporal processing, but is also involved in other processes, such as the estimation of quantity or numerosity. This neural circuit might be able to switch function between coincidence detection for estimating time, to spike counting for estimating numerosity". The ATOM proposal seems to be compatible with these classic models of magnitude processing, because they do not seem to require a unique, spatially characterized, and culturally influenced, representation as the MTL proposal does. We will now present some categories of studies supporting a unique system devoted to the processing of magnitudes, rather than a spatially characterized mental time line.

6.1. Interactions with physical size

The physical size of the stimuli influences their perceived duration. Magnitude information has been manipulated in Stroop-like paradigms, varying the number of dots or, alternatively, size or luminance of geometric shapes (Xuan et al., 2007; see Ono and Kawahara, 2007 for an alternative approach). These studies typically show that stimuli indexing larger magnitudes, not only in number, but also in size or luminance, are judged to last longer, whereas stimuli indexing smaller magnitudes are judged to last shorter (Xuan et al., 2007; see Matthews et al., 2011, for a discussion of the factors producing these interactions). One of the critical differences between estimates of temporal length and estimates of spatial length seems to be that the former can only be made at the end of stimulus presentation, while the latter can be made at any time during an exposure. A direct comparison suggests that people can efficiently estimate one duration at a time, whereas size estimation does not suffer so severely with increased number of distracters (Morgan et al., 2008).

In the Numerical Stroop task a response either to the numerical magnitude or to the physical size of a stimulus is typically required (Besner and Coltheart, 1979). The Numerical Stroop effect consists in an influence of the task-irrelevant physical size of Arabic digits on responses to numerical magnitude (and vice versa). Responses to congruent conditions, where the magnitude of a number is congruent with its physical size (e.g. a big number 9) are typically faster and more accurate than incongruent conditions (e.g. a small number "9"). The influence of numerical magnitude upon physical magnitude judgements increases during childhood as a function of schooling (Girelli et al., 2000).

6.2. Interactions between numbers and time

So far we have described interactions between the domain of space and time/number domains, in parallel. However, there is also evidence for direct interactions between numbers and time. These interactions have been described when the temporal dimension is presented in both "short–long" or "before–after" formats.

6.2.1. When "1" is short and "9" is long

This category encompasses studies that reported time–number interactions in the form of overestimation of perceived temporal duration when paired to relatively large numerical magnitudes and of underestimation when paired to relatively small magnitudes. For instance, the previously cited study of Xuan et al. (2007) varied not only number of dots, size and luminance of geometric shapes, but also the numeric magnitude of Arabic digits. They described an influence of the irrelevant numerical information (small–large) upon the perceived duration (perceived as shorter and longer, respectively). Similar results were reported by Xuan et al. (2009) using a variant of the Numerical Stroop paradigm. Participants compared the temporal durations of two Arabic digits displayed in the hundreds of milliseconds range. Their performance was more accurate when shorter durations were paired to small numbers and longer durations were paired to large numbers. This number–time interaction emerged also in a temporal duration comparison task with fixed standard (Vicario et al., 2008; Oliveri et al., 2008; Cappelletti et al., 2009, 2011a; see also Tokita and Ishiguchi, 2011).

Numerical magnitude can also prime the perceived duration of non-numerical stimuli (Vicario et al., 2008). The effect does not seem to generalize to all ordered sequences, because it does not emerge for letters of the alphabet, which convey ordinal information only (i.e., letters "early" vs. "late" in the alphabet; Oliveri et al., 2008).

This number–time interaction was shown to be influenced by framing the numerical magnitudes in specific contexts, as for instance a measure of weight (Lu et al., 2009; see also Lu et al., 2011). There is also evidence that numerical magnitude interacts with the temporal length of key-presses. Kiesel and Vierck (2009), for instance, asked participants to determine the parity of a digit by means of temporally long or short key-presses. Besides the fact that overall key-press durations were affected by number magnitude, faster responses emerged when small numbers required short key-presses and large numbers required long key-presses.

While numerical magnitude can interfere with duration processing, some studies failed to induce an interaction in the opposite direction, that is from temporal duration to numerical/quantity processing (Dormal et al., 2006; Cappelletti et al., 2009). Dormal et al. (2006) employed a variant of the Stroop paradigm in which a variable number of flashing dots was presented for different temporal durations. They found that the numerosity of the dots interfered with temporal duration judgements but not vice versa (see also Roitman et al., 2007).

This controversial issue was also addressed by Cappelletti et al. (2011a) in a neuropsychological study with two patients with parietal lesions. One had left hemisphere damage and presented with deficits for number processing and preserved time processing. Nonetheless her performance on time tasks was severely distorted by the mere presence of task-irrelevant numbers. A second patient had right hemisphere damage and selective impairment of time processing. His impaired temporal estimation was also influenced by preserved number processing: small numbers made time intervals appear shorter relative to large numbers, as in healthy participants. Both patients showed an influence of task-irrelevant number stimuli on time but not space processing.

A final example of the absence of interaction between numbers and temporal durations comes from the study of Agrillo et al. (2010). Participants were presented with several tones, differing in number and duration, and were asked to estimate either the duration of the stimulus or the number of tones. Results showed that estimates of duration were unaffected by number of tones, and estimates of numerosity were unaffected by duration; a finding incompatible with the possibility that time and numerosity might be processed by the same mechanism (but see Agrillo and Piffer, in press).

6.2.2. When "1" is before and "9" is after

This category encompasses studies that reported number–time interactions in the form of an association of small magnitudes with "before" responses and of large magnitudes with "after" responses (Müller and Schwarz, 2008; Schwarz and Eiselt, 2009). Schwarz and Eiselt (2009) used a temporal order judgement task in which the stimuli that were presented on the screen with variable asynchrony were pairs of numbers (one on the left and one on the right of fixation). Numerically smaller digits were perceived as occurring earlier in time with respect to numerically larger digits, even though the magnitude information was task-irrelevant.

This interaction seems to be also present when the mere order of stimuli is manipulated, with respect to both numbers and time. Müller and Schwarz (2008) showed that, in number comparison on sequentially presented digits, ascending pairs (such as 2–3) yielded faster responses than descending pairs (3–2), suggesting that judgments about numbers reflect the temporal numerical order in which they are presented (see Ben-Meir et al., in press, for a further characterization of the effect). Previous studies have shown that, upon presentation of two tones with different durations, responses were more accurate when the first tone was shorter or the second tone was longer (Conson et al., 2008) as if a preference for increasing temporal intervals would exist (see Lindemann et al., 2008, for a similar finding in the numerical domain). Nicholls et al. (2011) questioned the results of Schwarz and Eiselt (2009) and suggested that some associations between dimensions such as size, duration, and number can be in fact due to response biases rather than to the presence of common cognitive processes. Sometimes effects apparently due to a modulation upon perception are in fact due to response biases and/or task-specific methodological biases, rather than to the true nature of number–time interactions (Grassi and Bonato, 2012). Finally, a recent study has provided evidence for interactions, within a single paradigm, between numerical magnitude, size, and duration (Fabbri et al., 2012).

7. MTL vs. ATOM

Despite the fact that many studies refer indifferently to both MTL and/or ATOM proposals, the two accounts are not equivalent and differ for a number of predictions, some of which can be empirically tested (see Table 2). For instance, with respect to the level of interaction, the MTL hypothesis specifically assumes that time would be spatially represented, whereas ATOM is more concerned with a bidirectional overlap of magnitudes, whereby sensorimotor transformation for action preparation and not spatial representations would be the common metric for all magnitudes. The role of spatial attention, crucial in the MNL account of number–space interactions (Zorzi et al., 2012), would also be crucial for the MTL account, whereas (spatial) attention is irrelevant to ATOM. Studies in both numerical and time domains seem to indicate that spatial attention is the crucial mechanism for linking spatial representation with numerical or temporal quantities or concepts and that it might also be the medium for accessing and manipulating these spatial representations. This is consistent with the hypothesis that parietal spatial maps are "culturally recycled" (Dehaene and Cohen, 2007) and that spatial attention mechanisms are embedded within these spatial maps (Casarotti et al., 2012). Conversely, an action-related common system for magnitude processing does not imply a crucial role of spatial representations and it does not require spatial attention as a crucial medium.

Table 2
A comparison between MTL and ATOM proposals.

Characteristics	Mental time line	Common processing system ATOM
Representative studies	Di Bono et al. (2012) Ishihara et al. (2008); Müller and Schwarz (2008); Santiago et al. (2010); Weger and Pratt (2008)	Walsh (2003); Bueti and Walsh (2009)
Level of interaction	Spatial representation of time	Overlap of representations/processes
Role of spatial attention	Crucial	Secondary/unspecified
Quantities converge in . . .	Space	Space and time
Modulation by writing direction	Yes	No
Neural substrate	Parietal lobe	Parietal lobe
Accounts for deficits in neglect	Yes	No
Accounts for interactions between magnitudes	No	Yes
Level of explanation	More specific	More general
Role of sensorimotor transformations	Important	Crucial
Neural mechanism	Cultural recycling of spatial maps	Networks for sensorimotor transformation

The ATOM approach fits particularly well with quantity–duration interactions, because they are bidirectional (e.g., quantity influences duration and vice versa). In contrast, the MTL approach better accounts for the findings of impaired temporal processing in RHD patients because of their specific deficits in spatial/attentional processing. If the MTL hypothesis can be considered rather specific, ATOM is instead more general. Finally, both accounts identify in parietal lobe structures the neural locus of time–space interactions.

8. Neural bases of number/time processing and of interactions with spatial processing

8.1. Numbers

The current leading view in numerical cognition research posits that the horizontal segment of the bilateral intraparietal sulcus (hIPS) would be the neural correlate of an abstract representation of numerical magnitude (Fig. 4), whereas the bilateral posterior-superior parietal lobule is thought to implement attentional shifts upon the MNL (Dehaene et al., 2003, for review). The bilateral

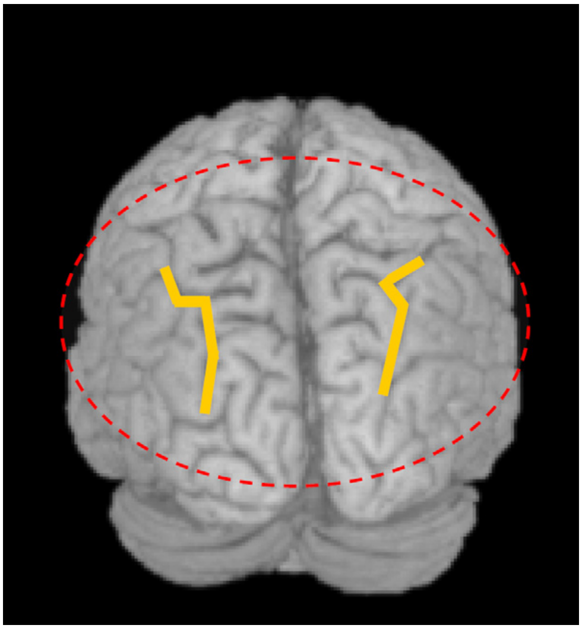

Fig. 4. A posterior-superior view of the human cerebral cortex. The ellipse indicates the parietal lobes, the orange lines, the intraparietal sulci. The parietal lobes are the cerebral substrate where, according to the ATOM proposal, time–space interaction takes place. The bilateral IPS is thought to be the neural substrate of the MNL and might be also a good candidate for the MTL.

hIPS is activated by numerical processing irrespective of the input format (verbal, Arabic, or non-symbolic; Eger et al., 2003; Piazza et al., 2007; but see Cohen Kadosh and Walsh, 2009, for arguments against abstract numerical representations). Single cell recording studies in behaving monkeys have revealed the existence of "number neurons" in fronto-parietal areas (Nieder and Dehaene, 2009, for review).

There is no published study to date that has revealed the neural basis of number–space interactions using fMRI. One exception is the study of Knops et al. (2009), who observed that mental arithmetic also recruits brain areas that are typically linked to the programming of eye movements and shifts of spatial attention. A hemodynamic signature of the SNARC effect in bilateral hIPS and left angular gyrus was recently highlighted by a functional Near Infrared Spectroscopy (fNIRS) study (Cutini et al., submitted for publication). TMS studies have suggested a key role for the frontal eye fields, the inferior frontal gyrus and the posterior parietal lobule in subtending number–space interactions (Sandrini and Rusconi, 2009, for review; Renzi et al., 2011). Finally, the temporal dynamics of numerically mediated shifts of attention have been explored using Event Related Potentials (ERP) (Priftis et al., 2008; Ranzini et al., 2009; Salillas et al., 2009). These studies highlighted that ERP components following the presentation of numbers closely resemble those traditionally associated with the orienting of spatial attention.

8.2. Order

It should be noted that the specificity of hIPS for numerical processing has been criticized by some authors, who found similar patterns of activation while processing numerical and non-numerical ordered sequences (Fias et al., 2007; Ischebeck et al., 2008), as if hIPS activation in tasks that involve the processing of numerical magnitude would be induced by the ordinal (rather than cardinal) dimension. This raises again the question of whether ordinality might be the common feature subtending the similarity between number and time and whether time is processed in the same network devoted to numbers. However, as noted before, this contention is challenged by neuropsychological dissociations between ordinal and magnitude judgments on numerical stimuli (Turconi and Seron, 2002), as well as by the finding that the apparent overlap in fMRI activation during processing of numerical and non-numerical order can be resolved into distinct voxel clusters by multivariate pattern classifiers (Zorzi et al., 2010).

The locus of ordered sequences representation might be determined by the nature of the stimuli rather than their ordinal nature (Van Opstal et al., 2009). In this study the left inferior frontal gyrus was involved in the processing of ordinal information, while there was no parietal area specifically dedicated to the representation of all ordinal sequences (see also Franklin and Jonides, 2009; Franklin et al., 2009).

8.3. Time

The neural correlates of time processing have been investigated in several fMRI studies (see Wiener et al., 2010, for a review). Wiener et al. (2010) report, in their metanalysis, that sub-second timing tasks show a higher propensity to recruit sub-cortical networks, such as the basal ganglia and cerebellum, whereas supra-second timing tasks are more likely to activate cortical structures, such as the supplementary motor area and prefrontal cortex. The possibility of different cognitive subsystems devoted to the processing stimuli quantitatively different is particularly well established in the domain of time processing (Ivry and Spencer, 2004; Lewis and Miall, 2006). Indeed, different mechanisms might underlie time perception in the milliseconds and in the supra-second intervals (e.g. Pöppel, 2009). Indeed one important caveat for the interpretation of the heterogeneous studies investigating cognitive and neural bases of time/(space) processing resides in the heterogeneity of the methods adopted. Time intervals adopted in both the behavioural and neuroimaging studies here reviewed are, for the time estimation tasks, ranging from a few hundred milliseconds to a few seconds. For the tasks involving real life temporal events, these might be up to the range of years (Arzy et al., 2009b). It is thus highly plausible that these different paradigms and intervals tap different mechanisms for time perception-estimation, but nonetheless it is also possible that all these mechanisms share a common spatial substrate.

There are several studies where time and memory are investigated. Despite the wide adoption of spatial metaphors (e.g. time travel) these papers did not directly investigate the time–space interactions. An example is provided by Szpunar et al. (2007), where participants underwent fMRI while using event cues (e.g., birthday) as a guide to imagine either a personal future event or remember a personal memory. Two main patterns of activation emerged. One network was more active while envisioning the future than while recollecting the past (right cerebellum and left premotor). A different network (bilateral posterior cingulated, bilateral parahippocampal gyrus, left occipital cortex) showed the same activity while envisioning the future and recollecting the past. The brain regions specifically recruited while envisioning future events were noted to be similar to those emerging from the literature on imagined bodily movements. Notably, the possibility of a unique single mechanism for the representation of the past and of the future would have, in contrast, predicted the recruitment of a similar network (see also Caruso et al., 2008).

Even more consistent in the use of spatial metaphors for data interpretation is the study by Arzy et al. (2009b). They maintain that "Human experience takes place in the line of mental time created through 'self-projection' of oneself to different time-points in the past or future" (p. 2009). In their study behavioural results and fMRI activation showed similarity between past recollection and future imagination and a distance effect with easier responses for timepoints "far from the present". The authors suggest that mental travel recruits similar areas and cognitive mechanism independently of whether real life episodes have to be re-experienced or pre-experienced.

Spatial and temporal aspects of psychophysical effects have been studied with fMRI by Assmus et al. (2003) and in monkeys by Leon and Shadlen (2003). Assmus et al. (2003) showed that the judgment about the possibility of collision between two moving objects (compared with size judgments) evoked activation in the supramarginal gyrus, as if this region, involved in programming skilled actions, would play a pivotal role in the integration of perceptual spatio–temporal information. Leon and Shadlen (2003) trained rhesus monkeys to respond to the temporal length of a briefly presented light with respect to a standard duration. They showed that processing of time took place in the posterior parietal cortex, an area primarily involved in space processing and sensorimotor integration, which in their study was found to encode also signals related to the perception of time.

It is however important to highlight that none of the above studies addressed the issue of the neural correlates of behavioural time–space interactions as defined in the present review. To our knowledge, there is no published fMRI study that directly investigated the time-space interactions we presented, but some hints are provided by TMS and ERP studies. Oliveri et al. (2009b) showed that TMS applied to the posterior parietal cortex induced, in healthy participants, underestimation of both temporal duration and line length in bisection tasks. In the same study, performance of neglect patients with lesions within the territory of the right middle cerebral artery showed underestimation of temporal duration and line length, thereby mirroring the consequences of parietal TMS in healthy participants. In another study (Oliveri et al., 2009a), rTMS of the right cerebellum selectively slowed responses to future tense of action verbs and rTMS of both cerebellar hemispheres decreased accuracy of responses to past tense in the left space and to future tense in the right space for non-verbs, and to future tense in the right space for state verbs. A recent ERP study (Vallesi et al., 2011) investigating the temporal dynamics behind the left–short right–long associations has revealed an early neural signature at the level of response preparation in the motor cortex developing for short stimuli first and then for longer ones.

In summary, the neural locus of time–space interactions is largely unknown, although, in analogy with the number–space interactions (Knops et al., 2009; Cutini et al., submitted for publication), the parietal cortex is surely the best (and, so far, the only) candidate (Bueti and Walsh, 2009). One difficulty, however, is the lack of a leading model of the cognitive bases of time–space interactions (unlike for number–space interactions). One obstacle towards a theoretical synthesis stems from the heterogeneity of the experimental paradigms and the extent of the investigated time intervals.

8.4. Number/time

Leaving aside the spatial aspects, some studies also directly addressed the neural correlates of number–time processing. Dormal et al. (2012) reported the activation, in an fMRI study, of a large right-lateralized fronto-parietal network, including the IPS and areas in the precentral, middle and superior frontal gyri by both numerosity and duration processing. The activation of the right IPS for both numerosity and duration tasks was considered to be evidence of a common magnitude processing system. With TMS technique, instead, Dormal et al. (2008) showed that the parietal area critically involved in numerosity processing is not involved in duration processing, thus maintaining that neural structures for duration and numerosity comparison can also dissociate.

9. Conclusions

The evidence reviewed here suggests that time interacts with spatial processing, in close analogy with number–space interactions. We have shown that the spatial effects found for numbers are indeed largely mirrored in the temporal domain. We have also highlighted that, when addressing time–space interactions, it is important to distinguish between studies adopting small vs. long durations or past vs. future temporal positions. We have argued that only the latter category of studies can be considered convincing evidence for a spatial representation of time. We have also discussed the tendency to transform in spatial terms abstract concepts, and the crucial – although not exclusive – role of writing direction in priming the direction of the association of time and number with space. Overall, there should be no doubt that the processing of time is not independent of the processing of space.

The hypothesis that time is represented in spatial format, akin to a MTL, is supported by a variety of studies employing different experimental paradigms. Notwithstanding the caveats discussed above, the MTL should be regarded as an explicit hypothesis of how time is mentally represented, or at the very least as a good metaphor to readily illustrate how temporal concepts and temporal flow are spatially represented.

An alternative account (ATOM) is also supported by several findings from both behavioural and cognitive neuroscience studies, which show multiple and bidirectional interactions across the domains of time, space and number magnitude.

Both accounts, however, need to be further developed and characterized to derive more straightforward predictions and therefore lead to new studies that might allow adjudication between them.

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