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Cognitive mapping in mental time travel and mental space navigation

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ABSTRACT

The ability to imagine ourselves in the past, in the future or in different spatial locations suggests that the brain can generate cognitive maps that are independent of the experiential self in the here and now. Using three experiments, we asked to which extent Mental Time Travel (MTT; imagining the self in time) and Mental Space Navigation (MSN; imagining the self in space) shared similar cognitive operations. For this, participants judged the ordinality of real historical events in time and in space with respect to different mental perspectives: for instance, participants mentally projected themselves in *Paris in nine years*, and judged whether an event occurred before or after, or, east or west, of where they mentally stood. In all three experiments, symbolic distance effects in time and space dimensions were quantified using Reaction Times (RT) and Error Rates (ER). When self-projected, participants were slower and were less accurate (absolute distance effects); participants were also faster and more accurate when the spatial and temporal distances were further away from their mental viewpoint (relative distance effects). These effects show that MTT and MSN require egocentric mapping and that self-projection requires map transformations. Additionally, participants' performance was affected when self-projection was made in one dimension but judgements in another, revealing a competition between temporal and spatial mapping (Experiment 2 & 3). Altogether, our findings suggest that MTT and MSN are separately mapped although they require comparable allo- to ego-centric map conversion.

1. Introduction

1.1. Mentally navigating space and time

The ability to integrate parts of the environment not immediately available to the senses rely on cognitive maps which provide an internal reference frame for mental events (Tolman, 1948). Mental events are internal representations linking specific contents to their position in space and time (Tulving & Donaldson, 1972; Suddendorf, Addis, & Corballis, 2009; Zacks & Radvansky, 2014). For instance, when a rat explores a maze, the spatiotemporal relationships between landmarks are encoded as internal distances between events (Gallistel, 1990; Gallistel & King, 2009; Poucet, 1993). In this example, internal distances encode the elapsed distance and the elapsed time between landmarks (i.e. the spatial and temporal dimensions of the environment, respectively). In other words, spatiotemporal encoding takes place as it is being experienced by the rat running through the maze. During maze navigation, such operations can be flexibly implemented in the brain, specifically in the hippocampal structures (Moser, Kropff, & Moser, 2008) in which place cells map space (Moser et al., 2008) whereas time cells and speed cells may map time (Eichenbaum, 2013; Kropff, Carmichael, Moser, & Moser, 2015). In the absence of overt movements, similar neural mechanisms are at play (Pastalkova, Itskov, Amarasingham, & Buzsaki, 2008). In humans, studies using virtual reality have suggested that the cognitive mechanisms used during actual spatial navigation may also be effective without motor displacement through the environment (Burgess, Becker, King, & Keefe, 2001; Doeller, Barry, & Burgess, 2010). One hypothesis is thus that the computational modules enabling navigation may operate in the absence of physical movement of the self through space or time.

In this context, we explored behavioral paradigms which required thinking about oneself navigating through space or time in the absence of any sensorimotor feedback. By navigating time, we mean the ability to envision the past and the future or Mental Time Travel (Tulving & Donaldson, 1972; Suddendorf & Corballis,

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Abbreviations: DE, Distance Effect; DIM, Dimension; DIST, Egocentric Distance; ER, Error Rate; m.d., mean difference; MTL, Mental Time Line; MTT, Mental Time Travel; MSN, Mental Spatial Navigation; RT, Reaction Time; SD, Spatial Distance; STREF, Spatio-Temporal reference; SWITCH, Switching Factor; TD, Temporal Distance; 2-AFC, Two-Alternative Forced-Choice.

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2007), which is a form of mental navigation in the temporal dimension. In a seminal work on Mental Time Travel (MTT) (Arzy, Molnar-Szakacs, & Blanke, 2008), participants judged whether a personal event occurred before or after a temporal reference that participants imagined or held in their mind. In the spatial analog of the MTT developed here which we call Mental Space Navigation (MSN), participants judged whether a historical event occurred east or west of a spatial mental reference.

Three experiments were designed to explore and compare MTT and MSN and to specifically test whether the temporal and spatial dimensions of mental events are integrated or independent features of event representation in the human mind.

1.2. Distance effects in time and space navigation

In seminal experiments, the more distant a stimulus is from its reference, the smaller the reaction time (RT) and the error rate. These so-called symbolic distance effects (DE) have been reported with a variety of stimuli (Moyer & Landauer, 1967; Moyer & Bayer, 1976; Shepard & Judd, 1976) and reported as *relative DE* in MTT when using a task in which participants classified an event as happening before or after a temporal reference (Arzy et al., 2008). A second effect, called *absolute DE,* was reported in which faster and more accurate responses were found when participants classified events from the present as compared to their past or future mental viewpoints. While comparable absolute DE have been considered to be "size effects" in the number literature (Parkman, 1971; Gallistel & Gelman, 1992; Feigenson, Dehaene, & Spelke, 2004; Verguts, Fias, & Stevens, 2005), they have been interpreted as correlates of "self-projection" in time indexing the imagery of the self at a different temporal location in MTT (Arzy, Adi-Japha, & Blanke, 2009; Arzy, Collette, Ionta, Fornari, & Blanke, 2009).

In the spatial domain, similar costs in RT have been reported in the spatial updating literature in virtual (Burgess et al., 2001) or real (Easton & Sholl, 1995; Mou, Mcnamara, Valiquette, & Rump, 2004; Rieser, 1989) environments, which both provided sensory and sensorimotor cues, respectively. Although seminal studies focused on the mental imagery of spatial geometric transformations (Shepard & Metzler, 1971; Kosslyn, Ball, & Reiser, 1978), less is known about purely mental spatial navigation.

The apparent similarities between temporal and spatial DE offers a simple way to investigate how far MTT and MSN are rooted in common cognitive processes. Similar to the quest for congruency effects between temporal, spatial and numerical domains in human behavior (Dehaene & Brannon, 2011; Gallistel & King, 2009; Walsh, 2003), the search for cross-dimension DE can shed new light on mental navigation in time and space.

1.3. Predictions

To investigate if common cognitive processes underlie MTT and MSN, we designed two tasks whose parameters were fully balanced across the temporal and spatial dimensions. The tasks consisted of temporal and spatial ordinality judgments using a 2-AFC. A unique set of stimuli or historical events was used in both tasks, and the overall task structure and requirements were identical. The experimental questions, design and predictions are illustrated in Fig. 1. Specifically, if common mental operations support MTT and MSN, we predicted the presence of absolute and relative distance effects relative to each dimension of the judgment. Additionally, and under the hypothesis of shared temporal and spatial cognitive maps, we predicted the presence of cross-dimension DE.

In Experiment 1, these predictions were independently tested for MTT and MSN in separate blocks (Fig. 1A, upper panel). We expected the presence of temporal and spatial DE in MTT and MSN, respectively, considering that temporal viewpoint changes were solely tested in MTT, and spatial viewpoint changes were solely tested in MSN (Fig. 1B). A common representation of time and space would predict cross-dimension relative DE (Fig. 1C). In Experiment 2 and 3, to maximize potential cross-dimension DE, MTT and MSN trials were intermixed within blocks (Fig. 1A, lower panel). If the representations of the temporal and spatial dimensions of mental events are distinct, a switch cost should be observed (Fig. 1D) and no cross-dimension DE should be observed. Conversely, setting a single spatio-temporal map would imply that switching from one dimension to the other should come at no cost but cross-dimension DE should be found (Fig. 1E).

2. Experiment 1: Absolute and relative distance effects in mental time travel and mental space navigation

2.1. Material and methods

2.1.1. Participants

Twelve subjects (6 males; mean age = 24.8 ± 6 years old) took part in the study. All were right-handed with corrected-to-normal vision and no history of psychological disorders. All participants lived in the Parisian region. All participants were compensated for their participation and provided written informed consents in accordance with the Ethics Committee on Human Research at the Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA, DRF/I^{2}BM, NeuroSpin, Gif-sur-Yvette, France) and the declaration of Helsinki (2008).

2.1.2. Stimuli and procedure

Visual stimuli consisted of high contrast white words centered on a black screen (mean length: 4.5°; mean width: 1.2°). Experiments were run in a darkened soundproof cabin. Participants were positioned on a headrest apparatus 70 cm away from a Viewsonic CRT monitor (19″, 60 Hz).

On the day prior to the experiment, participants were provided with a list of events with their historical description, dates and locations on a world map centered on Paris (HERE) (https://www.google.ca/maps, 01/06/2013). Participants were required to study the list and were informed that they will be tested on their acquired knowledge prior to the experiment. On the day of the experiment, they reported the events by filling a questionnaire and rated their recollection of each event by selecting "sure", "not sure", or "forgotten". The order of events presented in the list and during recollection was randomized across participants. MSN trials involving the judgment of forgotten geographical locations and MTT trials involving the judgements of forgotten dates were disregarded by masking RT and ER data with recollection hits.

During the experiment (Fig. 1A), participants were asked to mentally project themselves to a reference point in time or space and performed two possible tasks: in a 2-AFC Temporal Judgment task (MTT), they reported whether the event occurred before or after the projected mental reference; in a 2-AFC Spatial Judgment task (MSN), they reported whether the event occurred to the west or the east of the mental reference. For instance, in a given trial, participants were asked to project themselves 9 years ahead (FUTURE); they were then presented with a historical event (e.g. "Olympic games") and depending on the experimental block, performed a MTT or MSN task. Three MTT and MSN blocks were tested according to the three possible mental references in each category, namely: the three temporal references (T_{REF}) were "9 years ago" (PAST), today (NOW) and "in 9 years" (FUTURE); the three spatial references (S_{REF}) were Cayenne (WEST), Paris (HERE), and Dubaï (EAST).