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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,

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).

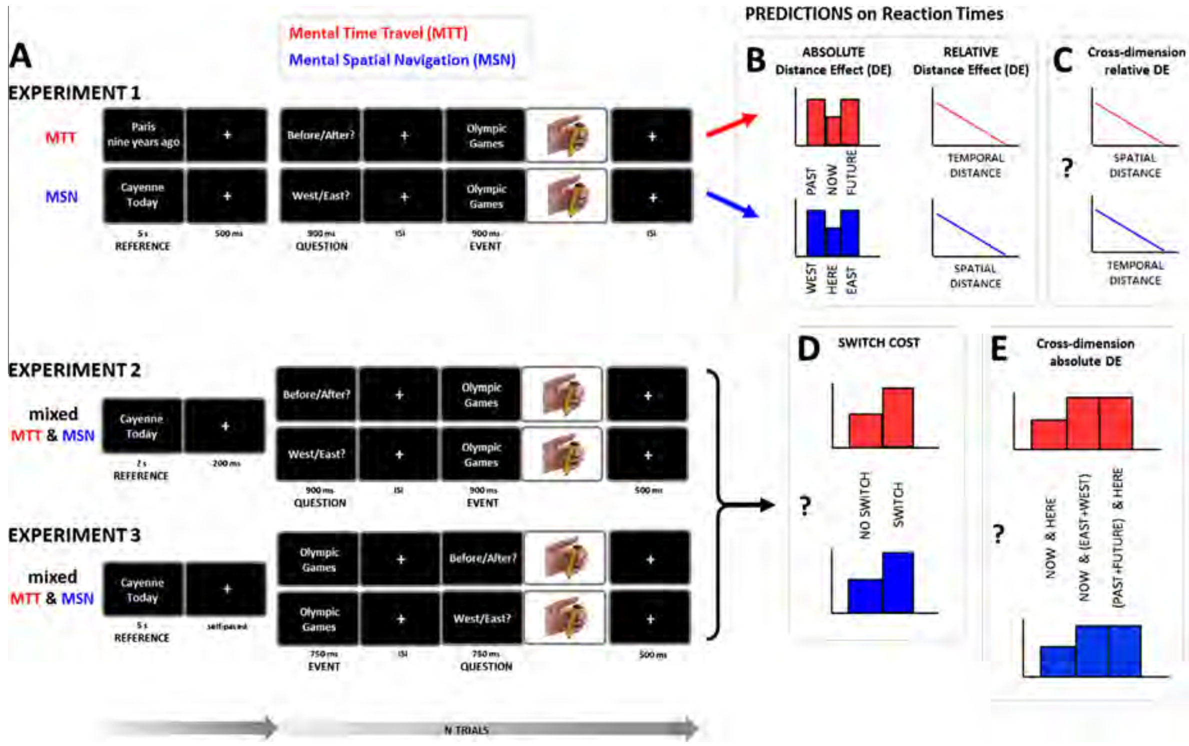


Fig. 1. Experimental paradigms and predictions. A. Experimental paradigms. In all three experiments, participants were asked to mentally project themselves to one of three possible temporal (PAST or "nine years ago", NOW, FUTURE or "in nine years") or spatial (WEST or "Cayenne", HERE, EAST or "Dubaï") references (REFERENCE). The presentation of the REFERENCE was followed by several successive trials. In Experiment 1 (top row), temporal (MTT, red) and spatial (MSN, blue) judgments were run in separate blocks; in Experiment 2 and 3, MTT and MSN were intermixed within the same blocks. In Experiment 1 and 2, the reference was followed by a 2-AFC question (QUESTION; MTT: "before/after?" or MSN: "west or east?"), itself followed by a historical event (EVENT); in Experiment 3, the QUESTION followed the EVENT. In Experiment1, only the temporal references were used for MTT and only the spatial references were used for MSN. B. Predictions and expected Reaction Times (RT) results. In Experiment 1, we wished to validate the paradigm by replicating the relative and absolute distance effects (DE) in Mental Time Travel (MTT, red) and to explore possible DE in Mental Space Navigation (MSN, blue). We predicted absolute DE in both tasks, i.e. faster RT in the "here and now" as compared to self-projected conditions (left panel). We also predicted relative DE in both tasks, i.e. faster RT with larger temporal and spatial distances irrespective of the reference (right panel). C. Predictions on space-time cross-dimension relative distance effects. If temporal and spatial dimensions are integrated features of an event representation, cross-dimension effects were predicted so that an increased temporal (spatial) distance will decrease RT during a spatial (temporal) judgment. D. Predictions on switch cost. To the contrary, if temporal and spatial dimensions are separate features of event representation, switching from one dimension (e.g. MSN) to another (e.g. MTT) in two successive trials should increase RT as compared to remaining in the same dimension in two successive trials. E. Predictions on absolute distance effects (DE). If temporal and spatial references are encoded in the same cognitive map, self-projection in one dimension (e.g. MSN) should equally affect judgments in the same (e.g. MSN) or in the other (e.g. MTT) dimension. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In a given block of Experiment 1, a T_{REF} or S_{REF} was displayed on the screen for 5 s during which participants could mentally project themselves. The reference was followed by 48 trials. Each trial consisted in a question presented on the screen for 900 ms and followed by a historical event for another 900 ms. The 2-AFC were "before/after" and "west/east" in MTT and MSN blocks, respectively. Judgments were performed with the right hand by pressing the key "I" or "P" on an 'azerty' keyboard. Importantly, response mapping was counterbalanced across runs so as to remove possible motor mapping confounds from the hypothesized mental mapping (Bonato, Zorzi, & Umiltà, 2012). Participants were given up to 4.5 s to provide their response before the next trial automatically started. The experimental instructions emphasized accuracy and speed equally. Each historical event was tested 6–10 times per judgment and per participant.

2.1.3. Statistical analysis

Statistical analyses were performed using Linear Mixed Effects models in R (R Foundation for statistical computing) and lme4 and LmerTest packages (Bates, Martin, & Bolker, 2012). In psychophysical analysis, subject-related variance is usually chosen as a random effect because of inter-individual variability, but inter-event variability is also difficult to control: each event has a range of parameters like fame, personal significance or word length. This is a typical issue in psycholinguistics, were either subject- or item-related variance can be modelled as a random effect (Clark, 1973). Rather than performing two different statistical testings, one for event-related effect and one for subject-related effect, we chose to conjointly account for subject- and item-related variance in our analysis (Baayen, Davidson, & Bates, 2008). Linear mixed models can be thought of as an extension of repeated-measures analyses of variances (ANOVA) as they model within-subjects and between-subjects variances separately. This means that, by considering that both subjects and events are drawn from a much larger population, we can generalize our findings to both subjects and events. Additionally, linear mixed models can fit models with both categorical and continuous predictors - here, the relative distance between reference and events - as in classic linear regressions. One small issue lies in the difficulty to represent combined variance components graphically, i.e. to choose the dimension of averaging the data. In this series of study, we chose to graphically represent the average across all repetitions of the minimal design (the combination of all combinations of conditions) with corresponding standard error bars, as statistics in mixed models are made from all individual observations. Importantly, this allows to visually estimate the shape of the effects and the variance across conditions but not to visually estimate the significance of the differences.

Linear mixed models were conducted for both continuous and categorical dependent variables (logistic model), namely reaction times (RT) and error rates (ER). In each tested model, random effects were modelled for subjects (SUBJ factor, 12 levels) and events (EVENT factor, 36 levels) in addition to fixed effects. Three fixed effects were considered for each of the 4 possible models (RT_{MTT}, RT_{MSN}, ER_{MTT}, ER_{MSN}): (1) the spatiotemporal reference (categorical predictor, 3 possible levels for T_{REF} and $S_{REF,}$ namely: PAST, NOW, FUTURE and WEST, HERE, EAST, respectively), (2) the absolute value of the relative temporal distance (TD: continuous predictor) and (3) of the relative spatial distance (SD: continuous predictor) between the event and the reference. In the RT models, only correct trials were analyzed (accounting for 88% of RT data, see Section 2.2).

Prior to statistical analysis, RTs were log-transformed to symmetrize the skewed distribution and the reported results were back-transformed, accordingly. As in typical ANOVAs, adding more and more predictors can underestimate significant effects due to an over-fitting of the data. To circumvent this issue, we used a statistical model selection strategy based on Akaike Information Criterion (AIC) score. We used a forward model selection strategy, starting from a null model containing only random effects and iteratively selecting fixed effects giving with lowest AIC and passing a χ^2 test (alpha = 0.05) compared to previous model (Supplementary Fig. 3). The equivalent of planned comparisons and post hoc tests were then derived from the selected final model with LmerTest package using t-tests for RT models and Wald test for ER models, based on Satterwaithe approximation for degree of freedom. For that part, reported p-values were relative to an intercept baseline condition chosen here to be the physical references, namely: T_{REF} = NOW in TOJ and S_{REF} = HERE in SOJ and estimated with a Markov Chain Monte Carlo (MCMC) (Baayen et al., 2008).

Table 1
Linear mixed model selections for reaction times (RT) and error rates (ER) produced in Mental Time Travel and Mental Space Navigation (MTT and MSN, respectively). T_{REF} is the mental reference in MTT; S_{REF} is the mental reference in MSN. TD and SD are the temporal and spatial distances, respectively. Only those models showing significant or marginal effects compared to previous models are reported for clarity. The selected models for significant effects are shown in bold. The RT_{MTT} table (upper table) reports the significant main effects of TD on RT observed in MTT; the RT_{MSN} table (second table) reports significant main effects of SD on RT in MSN. The ER_{MTT} table (third table) reports significant effects of temporal distance and temporal reference on ER (odd ratios) in MTT; the ER_{MSN} table (bottom table) reports the significant main effects of spatial distance and reference on ER (odd ratios) in MSN. In all four cases, significant effects of the reference (T_{REF}, S_{REF}) and the distance (TD, SD) in the tested dimension were observed. Importantly, no interactions were found between spatial and temporal dimensions. ** p < 0.01; *** p < 0.001.

	Df	AIC	logLik	Chisq	Pr(>Chisq)
RT_{MTT} MODEL					
Model0 = (1|SUBJ) + (1|EVENT)	4	11,076	−5533.9		
Model1 = Model 0 + T_{REF}	5	11,053	−5521.3	25.2715	4.980e−07***
model2 = Model1 + TD	**7**	**11,026**	**−5506.2**	**30.1215**	**2.879e−07*****
model3 = Model2 + $T_{REF} * TD$	9	11,025	−5503.5	5.5309	0.06295
RT_{MSN} MODEL					
Model0 = (1|SUBJ) + (1|EVENT)	4	11,908	−5950.3		
Model1 = Model 0 + S_{REF}	5	11,894	−5941.8	16.8311	4.086e−05***
model2 = Model1 + SD	**7**	**11,888**	**−5936.9**	**9.8251**	**0.007354****
model3 = Model2 + $S_{REF} * SD$	9	11,887	−5934.6	4.6771	0.096467
ER_{MTT} MODEL					
Model0 = (1|SUBJ) + (1|EVENT)	3	3734.8	−1864.4		
Model1 = Model 0 + T_{REF}	4	3692.8	−1842.4	43.974	3.328e−11***
model2 = Model1 + TD	6	3685.4	−1836.7	11.430	0.003297**
model3 = Model2 + $T_{REF} * TD$	**8**	**3678.3**	**−1831.1**	**11.157**	**0.003778****
ER_{MSN} MODEL					
Model0 = (1|SUBJ) + (1|EVENT)	3	4859.0	−2426.5		
Model1 = Model 0 + S_{REF}	4	4688.5	−2340.3	172.490	<2.2e−16***
model2 = Model1 + SD	6	4678.2	−2333.1	14.337	0.0007706***
model3 = Model2 + $S_{REF} * SD$	**8**	**4672.1**	**−2328.1**	**10.089**	**0.0064451****

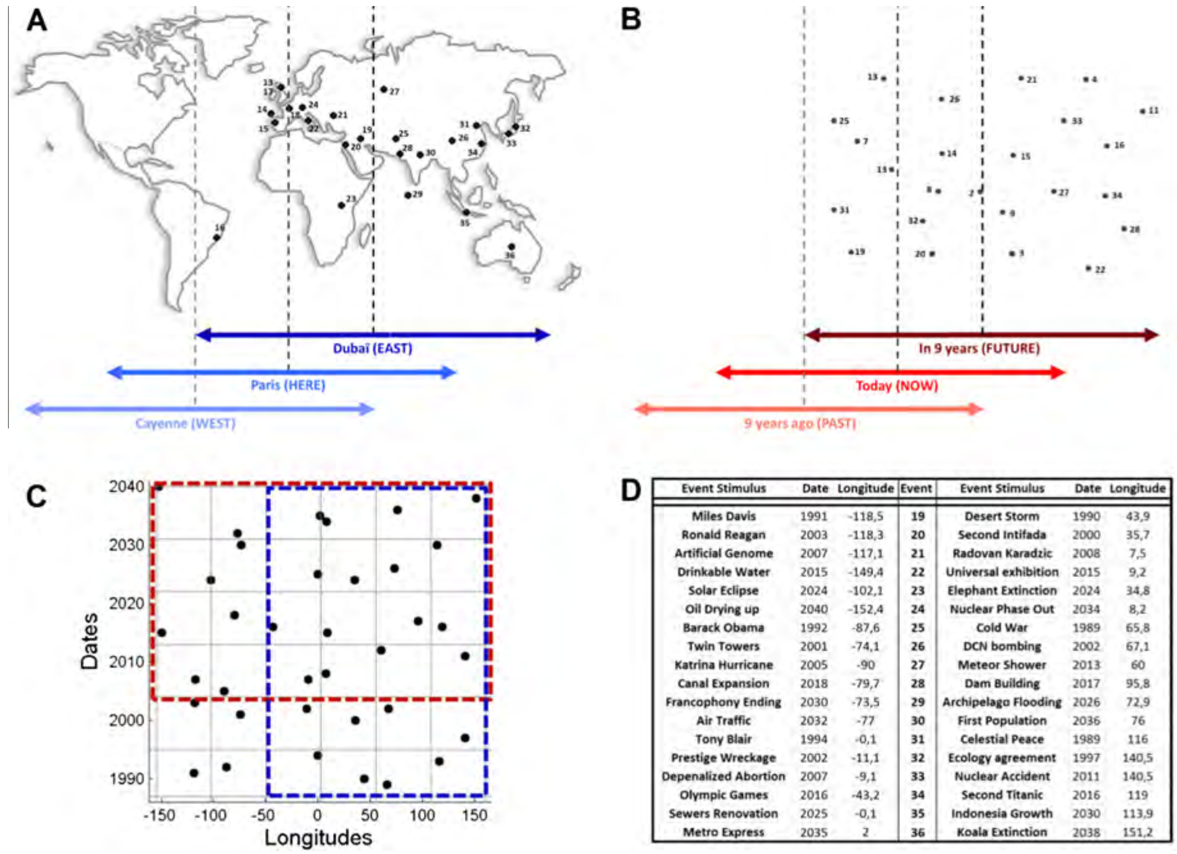
2.2. Results

We replicated the absolute and relative distance effects (DE) in the temporal judgement task (Arzy, Adi-Japha et al., 2009) and extended these findings to the spatial domain. Relative DE was found to be domain-specific so that a change in temporal (spatial) reference did not affect spatial (temporal) judgments. However, relative DE was found to unexpectedly interact with absolute DE. The reported main effects were driven by the model selection (Table 1) followed by planned comparisons and post hoc tests.

First and prior to the analysis, about 11% of events were disregarded due to participants not responding, replying "forgotten" or misreporting the date or location of the event. On average, participants were 88% correct in locating events on the map (7% of outside the country they belong to, and 5% were light misplacements) and 83% correct in recalling the historical dates (mean deviation: 0.6 years). Additionally, the more future the events, the less remembered they were (logistic regression, $z = 2.8$, $p < 0.01$). This effect was not observed for spatial distances.

2.2.1. Absolute DE are observed in mental time travel and in mental space navigation

Significant effects of self-projection were found in RT models (T_{REF} for RT_{MTT} and S_{REF} for RT_{MSN}, Table 1). Planned comparisons showed that participants took significantly longer to respond from a PAST or FUTURE mental viewpoint than from the NOW viewpoint in MTT (Fig. 3A): a significant mean difference of +115 ms was found between RT in PAST and in NOW ($t(2495) = 5.39$, $p < 0.001$), and of +76 ms between FUTURE and NOW ($t(2731) = 3.44$, $p < 0.005$) mental viewpoints. Post-hoc t-tests contrasting PAST and FUTURE did not reach significance. Similarly in MSN, RT were significantly longer for WEST (m.d. = 66 ms, $t(3228) = 2.73$, $p < 0.01$) and EAST (m.d. = 110 ms, $t(2913) = 2.56$, $p = 0.01$) as compared to HERE references (Fig. 3A). Post-hoc t-tests contrasting WEST and EAST references did not reach significance. These results indicate that during the MTT task, mentally traveling in time from a mental past or future viewpoint takes longer than from the now viewpoint; conversely, mentally navigating space (MSN) from a west or east viewpoint takes longer than from the here viewpoint. These first results suggest that participants did mentally self-project in different mental viewpoints. Similar effects were observed for ER models (ER_{MTT} and $ER_{MSN,}$ Table 1). Planned comparisons showed that participants made significantly more errors in their response from the PAST (m.d. = 0.02, $z(2495) = 3.72$, $p < 0.001$) and FUTURE (m.d. = 0.018, $t(2731) = 2.27$, $p < 0.05$) as compared to the NOW reference (Fig. 3B). Post-hoc t-tests contrasting the odd ratios in PAST and FUTURE reference trials did not reach significance. Similarly in ER_{MSN}, odd ratios increased significantly for WEST (m.d. = 0.025, $z(3559) = 2.1$, $p < 0.05$) and EAST (m.d. = 0.039, $z(3328) = 4.3$, $p < 0.001$ respectively) reference trials as compared to the HERE trials (Fig. 3B). Post-hoc t-tests contrasting the odd ratios in WEST and EAST reference trials did not reach significance. Overall, mental



Event Stimulus	Date	Longitude	Event	Event Stimulus	Date	Longitude
Miles Davis	1991	-118,5	19	Desert Storm	1990	43,9
Ronald Reagan	2003	-118,3	20	Second Intifada	2000	35,7
Artificial Genome	2007	-117,1	21	Radovan Karadzic	2008	7,5
Drinkable Water	2015	-149,4	22	Universal exhibition	2015	9,2
Solar Eclipse	2024	-102,1	23	Elephant Extinction	2024	34,8
Oil Drying up	2040	-152,4	24	Nuclear Phase Out	2034	8,2
Barack Obama	1992	-87,6	25	Cold War	1989	65,8
Twin Towers	2001	-74,1	26	DCN bombing	2002	67,1
Katrina Hurricane	2005	-90	27	Meteor Shower	2013	60
Canal Expansion	2018	-79,7	28	Dam Building	2017	95,8
Francophony Ending	2030	-73,5	29	Archipelago Flooding	2026	72,9
Air Traffic	2032	-77	30	First Population	2036	76
Tony Blair	1994	-0,1	31	Celestial Peace	1989	116
Prestige Wreckage	2002	-11,1	32	Ecology agreement	1997	140,5
Depenalized Abortion	2007	-9,1	33	Nuclear Accident	2011	140,5
Olympic Games	2016	-43,2	34	Second Titanic	2016	119
Sewers Renovation	2025	-0,1	35	Indonesia Growth	2030	113,9
Metro Express	2035	2	36	Koala Extinction	2038	151,2

Fig. 2. Temporal and spatial properties of the events set used in Experiment 1. A: Example of the spatial distribution of historical events used in the spatial judgment (MSN) task for the Dubaï (EAST) reference. B: Example of the temporal distribution of historical events used in the temporal judgment (MTT) task for the "in nine years" (FUTURE) reference. C: Spatiotemporal matrix illustrating the distribution of the full set of historical events used in Experiment 1. The blue rectangle provides the limits for the EAST reference set showed in panel A; the red rectangle provides the limits for the FUTURE reference set showed in panel B. D: Full list of the 36 historical events with their dates and longitudes. Note that the historical events were provided in French. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

self-projections in time and space increased the ER as compared to the now and here.

2.2.2. Relative DE are dimension-specific

Significant relative DE was observed in RT models (TD for RT_{MTT} and SD for RT_{MSN}, Table 1). In Fig. 3C (left panel), RT were plotted as a function of the relative temporal distance from the reference for all three T_{REF}: as can be seen, the temporally closer an event was to the T_{REF}, the slower the RT (slope = −0.008 ± 0.003 s/year). This was observed irrespective of T_{REF}. Importantly, the spatial distance of an event from T_{REF} did not affect response times during MTT: in other words, no effect of relative spatial distance was found on RT_{MTT}. Similarly in RT_{MSN} (Fig. 3C, right panel), the spatially closer an event was to the S_{REF}, the slower the RT (slope = −0.0013 ± 0.0005 s/°). This effect was observed irrespective of S_{REF} and was not affected by temporal distance. Relative DE was also found for error rate models (ER_{MTT} and ER_{MSN}, Table 1). Fig. 3D (left panel) shows ER_{MTT} plotted as a function of relative spatial distance from the reference for all T_{REF} levels. Consistent with the pattern of RT, the closer the event was to T_{REF}, the less accurate participants were (slope = −0.07 ± 0.01 odd ratio/year; z = -7, $p < 0.001$). Whether an event was located far or close in space did not affect the odds ratio. Similarly in ER_{MSN}, the more spatially distant events were from S_{REF}, the more errors participants made (slope = −0.02 ± 0.001 odd ratio/°; z = −12, $p < 0.001$, respectively). This effect was not affected by temporal distance.

Taken together, these results show that the farther away an event was from the temporal and spatial mental viewpoint (T_{REF} or S_{REF}, respectively), the faster and the more accurate participants were in their temporal and spatial judgments, respectively. This pattern was consistent with our general predictions (Fig. 1B, right panel). Crucially, the spatial dimension did not significantly affect the speed or the accuracy of participants during MTT and conversely, the temporal dimension did not significantly affect the speed or the accuracy of participants during MSN: this goes against the prediction that cross-dimension effects can be observed in relative DE (Fig. 1C).

2.2.3. Absolute and relative DE interact in error rates

In both MTT and MSN tasks, significant interactions were found between absolute and relative DE in error rate models (ER_{MTT} and ER_{MSN}, Table 1). Fig. 3E (left panel) provides the relative DE observed in temporal judgments as a function T_{REF}. As described earlier, relative DE were observed for each possible T_{REF} so that the more temporally distant the event, the lower the odds ratio. However, and interestingly, when the T_{REF} was NOW, the odds ratio decreased more slowly than when it was PAST or FUTURE. The relative temporal DE was thus significantly stronger in PAST as compared to NOW (z = −3.17, $p < 0.005$) but failed to reach significance for FUTURE (z = −1.15, p = 0.25). Similarly, Fig. 3E shows the spatial relative DE as a function of S_{REF} in which the odds ratio decreased more slowly in HERE than WEST or EAST references. A significant increase of the slope was observed for both WEST (z = −2.06, $p < 0.05$) and EAST (z = −2.94, $p < 0.005$) as compared to HERE (Fig. 3E).

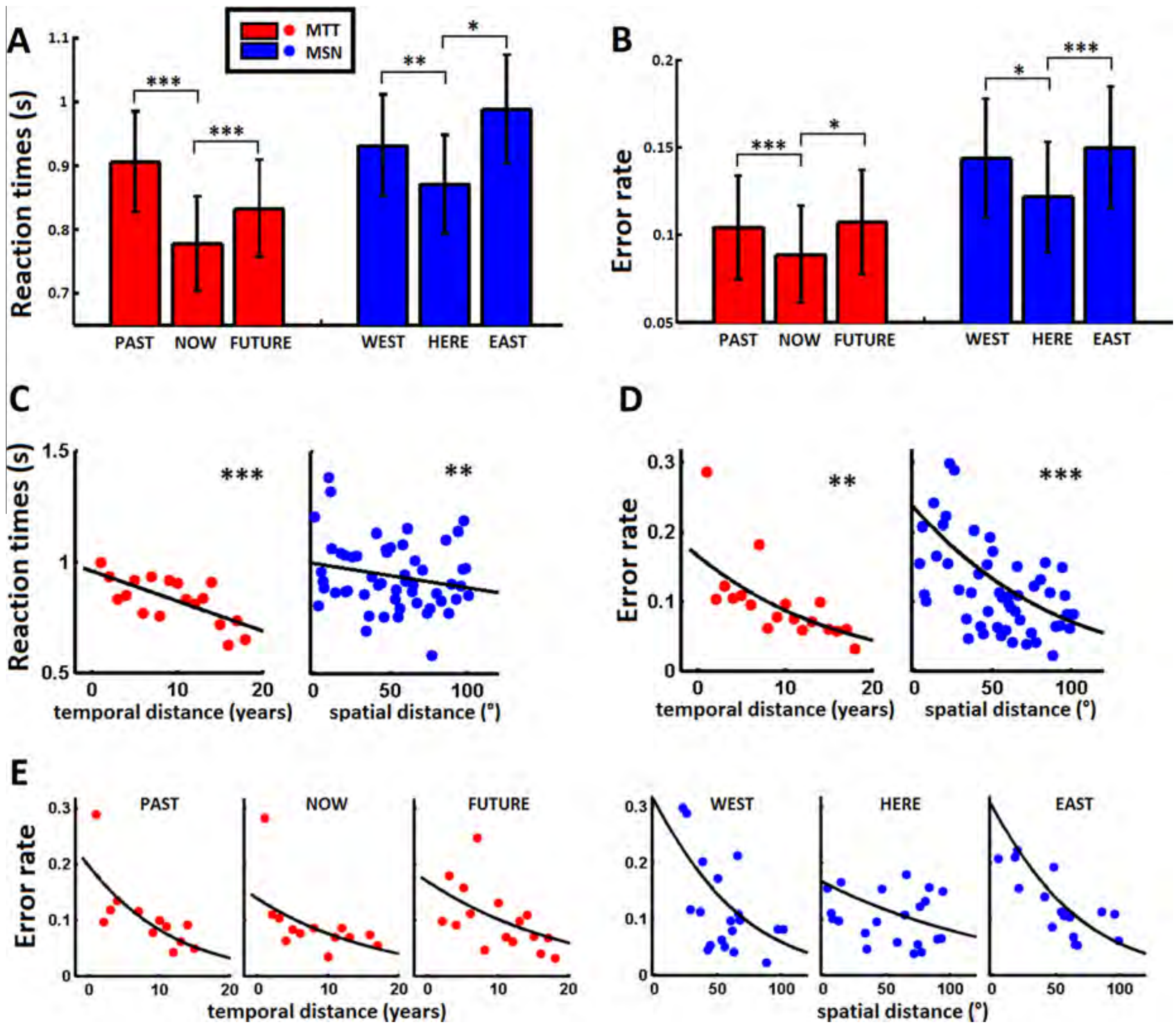


Fig. 3. Absolute and relative distance effects in Mental Time Travel (MTT) and Mental Space Navigation (MSN). A. Absolute Distance Effects (DE) as measured by reaction times (RT). Mean RT as a function of the temporal and spatial reference in the temporal and spatial judgment tasks (MTT and MSN, red and blue, respectively) collapsed across all other dimensions. A mental viewpoint differing from NOW and HERE significantly increased RT. Mean values are average across repetitions and error bars are ±1 s.e.m. B. Absolute DE as measured by Error rates (ER). ER as a function of the temporal and spatial references in MTT and MSN, respectively. Mean values are average across repetitions and error bars are ±1 s.e.m. A mental viewpoint differing from NOW and HERE significantly increased ER. C. Relative DE as measured by RTs. Mean RT as a function of the temporal and spatial distances of the historical event from the reference. Black lines are linear regressions. D: Relative DE as measured by ER. Mean ER as a function of temporal (red) and spatial (blue) distance. Black lines are logistic regressions, as statistics were performed on binomial (success/failure) data. E: Mean ER as a function of temporal (red) and spatial (blue) distance and references. The steepness of the decrease was significantly smaller in NOW as compared to PAST but not FUTURE; the steepness of the ER decrease was significantly smaller in HERE as compared to WEST and EAST. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

These interactions draw a novel relationship between absolute and relative DE, specifically: for the same veridical (temporal or spatial) distance, judgments performed in a mentally projected reference (e.g. PAST or WEST) yielded more errors than in the non-projected reference (i.e. NOW or HERE). These results were not predicted from our initial working hypotheses and constitute a novel observation.

2.3. Discussion

Experiment 1 replicated absolute DE in time and extended absolute DE to the spatial dimension in a novel MSN task. These results indicate that MTT and MSN rely on a self-projection operation that comes with a cognitive cost: in these tasks, events are not simply retrieved from memory but also manipulated in a dedicated self-related cognitive map. Second, we replicated relative DE in MTT and found relative DE for MSN. Relative DE suggests a relative mental mapping of events even though our ordinality tasks did not explicitly require the manipulation of distances. Additionally, a significant interaction between absolute and relative DE in both dimensions was found: self-projection increased the negative slope in ER as a function of distance. This interaction suggests that self-projection and symbolic distances are bound to the same map. No cross-dimension relative DE was found (Fig. 1C), suggesting that temporal and spatial metrics may be represented independently. Still, some limitations in the design of Experiment 1 may have prevented such interactions to be detected: first, the distribution of historical events slightly differed between MTT and MSN blocks because the number of events in relative past/future (west/east) for MTT (MSN) task had to be balanced around each reference (e.g. around FUTURE and EAST reference (Fig. 2C)), preventing the use of a unique statistical model accounting for dimension-by-distance interaction. In Experiment 2, we ensured that all combinations of references and events were tested in MTT and MSN. Second, Experiment 1 investigated self-projection in time only during MTT and in space only during MSN, minimizing the potential for cross-dimension effects. To circumvent this issue, a second experiment was designed in which MTT and MSN were intermixed within blocks.

3. Experiment 2: Cross-dimension space-time effects are found for absolute but not for relative DE

3.1. Material and methods

3.1.1. Participants

19 subjects (9 males; mean age = 24 ± 4 years old) participated in Experiment 2. All participants were right-handed with corrected-to-normal vision and no history of psychological disorders. All participants lived in the Parisian region. The ethical protocols and compensations were identical to Experiment 1.

3.1.2. Stimuli and procedure

Behavioral data were acquired during a dedicated neuroimaging experiment. Visual stimuli were projected on a screen placed 90 cm away from participants seated in a magnetoencephalographic system (Neuromag Elekta LTD, Helsinki). Responses were recorded using two FORP button response pads (FORP systems, Inc.). The pre-experimental procedure was identical to Experiment 1. During Experiment 2 (Fig. 1A) participants performed the same tasks as in Experiment 1 and in a given block, MTT and MSN trials were randomly alternated. Each block consisted of 8 trials. 36 events were presented with the reference "Paris, today" and 24 events were presented with the other references centered on the same spatial and temporal reference points as those used in Experiment 1 (Fig. 2A and B). This insured that, for each reference condition, an equal number of events happened before and after, and west and east of the reference point. This also ensured that all events were presented in the baseline HERE and NOW condition (Present, Paris).

3.1.3. Statistical analysis

Two different linear mixed models were defined to test for the existence of DE and switch costs using RT and ER data. In both models, and as previously described, the factors SUBJECT and EVENT were accounted for by random effects.

First, four factors were used to investigate DE. To the two continuous factors TD and SD previously used in Experiment 1, we added two new categorical factors: the factor DIM combined the temporal and spatial dimension (2 levels: MTT and MSN) in order to capture DE irrespective of the dimension and to assess possible interactions across dimensions. A second factor called STREF (for spatiotemporal reference) was introduced which combines the two REF factors used in Experiment 1 (T_{REF} and S_{REF}). STREF had 3 possible levels: TProj for self-projection in time combining PAST and FUTURE, Sproj for self-projection in space combining WEST and EAST and NoProj for no self-projection (namely, the HERE and NOW reference). This was done to test the interaction between STREF and DIM and thus to test two working hypotheses illustrated in Fig. 1B (left panel) and E. This approach was further motivated by the lack of significant differences between PAST and FUTURE, and WEST and EAST in Experiment 1. Second, thanks to the intermixing of MSN and MTT trials within blocks, we could now ask whether switching dimension from one trial to the next would be associated with a cognitive cost. To test this, a dedicated model was built and a new factor SWITCH was introduced (2 levels: switch and no switch). In "switch", the preceding trial was a MTT (MSN) and the next trial was MSN (MTT) and in "no switch", successive trials required a judgment along the same dimension. This new model excluded the factors of distance (TD, SD) because SWITCH was unbalanced with respect those ones; this was also the reason why two separate models were elaborated to test DE and switch cost. Three categorical factors were thus tested: STREF, DIM and SWITCH. Specific predictions of switch cost effects in Experiment 2 are illustrated in Fig. 1D. For each model, all factors of interest (Table 2) underwent AIC-based selection (Supp. Table 2) and planned comparison and post hoc p-values were derived from the final model.

3.2. Results

In Experiment 2, both RT and ER obtained in MTT and MSN replicated the patterns of absolute and relative DE observed in Experiment 1. Additionally, we report two novel interactions between the temporal and spatial dimensions.

On average, participants were 88% correct in locating events on the real world map (3% of locations were placed outside the actual country they belonged to, and 9% were light misplacements) and 91% correct in recalling the historical dates (mean error deviation: 0.2 years). Spatial locations of past events (i.e. before 01/01/2013) were slightly less well remembered than future ones (logistic model, mean difference (m.d. = 5.3%, $z = -1.92$, $p = 0.048$). Similar to Experiment 1, recall errors were more frequent for future than for past events (m.d. = 5.1%, $z = 2.2$, $p = 0.031$) and for events located at the east of Paris as compared to the west (m.d. = 6.7%, $z = 2.9$, $p < 0.01$). Hence, 10.5% of the data were disregarded. This was comparable to Experiment 1.

Adding a DIM factor significantly improved RT_{SWITCH} and RT_{DIST} models (Table 2). However, the estimation of the main effect of DIM inside these two models fail to reach significance ($t = 1.48$, $p = 0.92$ and $t = 0.09$, $p = 0.14$ respectively).

3.2.1. Switching between MTT and MSN increases RT

A significant effect of dimension SWITCH was observed in the dedicated model RT_{SWITCH} (Table 2). Planned comparisons showed that switching dimension increased RTs, whether switching from MSN to MTT or from MTT to MSN (m.d. = 184 ms, $t = 6.51$, $p < 0.001$ and m.d. = 82 ms, $t = 2.82$, $p = 0.005$, respectively, Fig. 4A). However, the switch cost appeared to be more pronounced when switching from a spatial to a temporal judgement as compared to switching from a temporal to a spatial judgement. Congruent with this observation, a significant interaction between the SWITCH and the dimension (DIM) confirmed longer RT when switching from MSN to MTT trials as compared to switching from MTT to MSN trials (m.d. = 102 ms, $t = 2.79$, $p = 0.005$). In Experiment 2, and contrarily to Experiment 1, participants could be asked to project themselves in a spatial location that differed from "here" (Sproj) but be subsequently asked a temporal judgement. Conversely, participants could mentally project themselves at a different time (Tproj) and be subsequently asked a spatial judgement. This balanced design enabled us to directly assess whether mental projection in one dimension affected judgements in the other dimension by quantifying the SWITCH-by-DIM interaction as a function of the self-projection conditions (STREF). This triple interaction significantly improved the RT_{SWITCH} model (Table 2). The increase in RT observed when switching from the temporal to the spatial dimension was equivalent in all self-projection conditions (NoProj:+96 ms; Tproj:+89 ms; Sproj:+62 ms). On the other hand, the increase in RT observed when switching from the spatial to the temporal dimension tended to be smaller in Tproj as compared to NoProj or Sproj but failed to reach significance (Tproj: +109 ms; *vs.* NoProj:+195 ms, $t = -1.72$, $p = 0.084$; *vs.* Sproj: +261 ms, $t = 1.73$, $p = 0.084$).

No switch effects accounted for the ER data (Table 2 and Fig. 4B).

Table 2
Linear mixed models selected for each experiment. An effect (rows) included in a model (columns) after the selection step is indicated by a checkmark. Slots highlighted in grey are effects that we could not or purposely did not test for a given model (see Materials and methods section for each experiment). Models were used to compute p-values for planned comparisons and post hoc tests reported in the Results section of each experiment. Selected Factors. DIM: dimension of the task; STREF: spatiotemporal reference; SWITCH: task switch cost; TD: temporal distance; SD: spatial distance. Models. For experiment 1: temporal and spatial judgment (MTT and MSN) were modelled separately. For experiment 2 and 3, they were modelled jointly. RT_{MTT} and ER_{MTT}: reaction time and error rate models of MTT; RT_{MSN} and ER_{MSN}: reaction time and error rate models of MSN; RT_{SWITCH} and ER_{SWITCH}: reaction time and error rate models of MSN and MTT for switch effects; RT_{DIST} and ER_{DIST}: reaction time and error rate models of MSN and MTT for distance effects.

	Experiment 1				Experiment 2				Experiment 3	
Variable	RT		ER		RT		ER		RT	ER
Model	MTT	MSN	MTT	MSN	SWITCH	DIST	SWITCH	DIST	DIST	DIST
Selected Factors										
DIM					∨	∨			∨	∨
STREF (T_{REF}, S_{REF})	∨	∨	∨	∨	∨	∨	∨	∨	∨	∨
SWITCH					∨					
TD	∨		∨			∨		∨	∨	∨
SD		∨		∨		∨		∨	∨	∨
STREF :DIM					∨	∨	∨	∨	∨	∨
SWITCH :DIM					∨					
TD :DIM						∨		∨	∨	∨
SD :DIM						∨		∨	∨	∨
STREF :TD			∨					∨	∨	
STREF :SD				∨				∨		∨
SWITCH :STREF :DIM					∨					
STREF :SD :DIM						∨		∨		∨
STREF :TD :DIM						∨		∨	∨	∨
STREF :TD :SD										∨

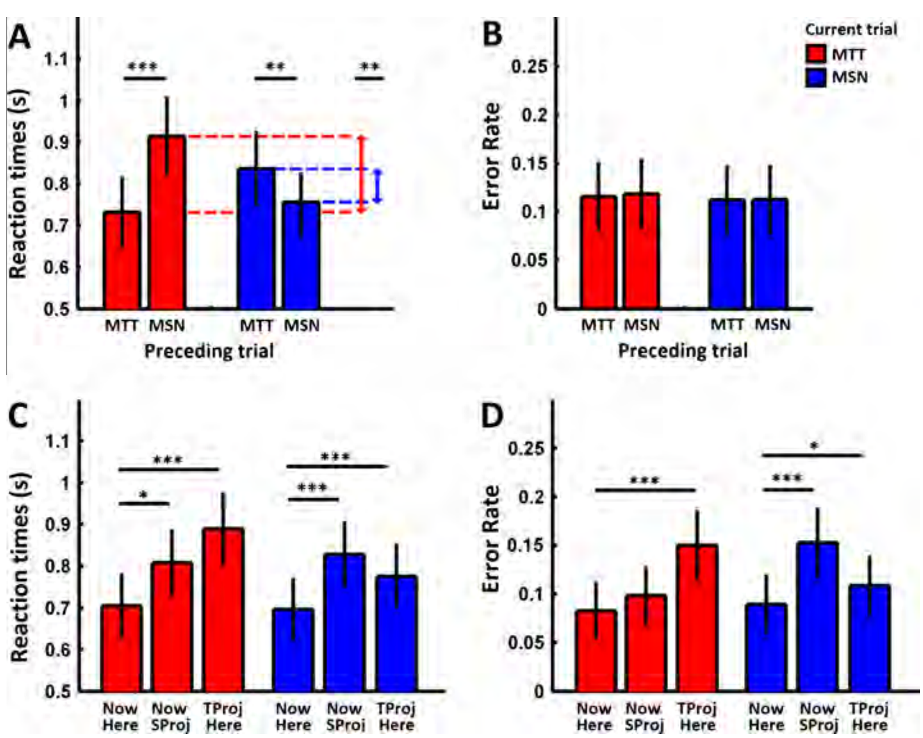


Fig. 4. Space-time cross-dimension effects in switch cost and absolute distance. A. Switch cost of reaction times: larger cost when switching from temporal to spatial than from spatial to temporal judgments. MTT performed after a MSN (right red bar) took longer than those after a MTT (left red bar). Similarly, MSN performed after a MTT (left blue bar) took longer than those after a MSN (right blue bar). The switch cost was significantly larger for MTT than for MSN (red arrow *vs.* blue arrow). B. No switch cost in error rates: No significant effect of switch cost was found in ER. C. Cross-dimension absolute distance effect in RT: Self-projection in time (Tproj) significantly increased RT for MTT (red) as compared to "Now Here" condition; self-projection in space (Sproj) significantly increased RT for MSN (blue) as compared to the "Now Here" condition. This pattern matched the prediction of a dimension-specific absolute DE. Additionally, and unexpectedly, a dimensionless absolute DE was also observed, in which Tproj increased RT for spatial judgements and Sproj increased RT for temporal judgements as compared to the "Now Here" condition. D. Dimension-specific absolute DE of error rates: Self-projection in time (Tproj) significantly increased ER for MTT (red) as compared to "Now Here" condition; self-projection in space (Sproj) significantly increased RT for MSN (blue) as compared to the "Now Here" condition. A dimensionless absolute DE was also observed for MSN only. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Absolute DE capture space-time cross-dimension effect

A significantly better fit of RT_{DIST} model was found by including STREF effect (Table 2). Planned comparisons showed significantly larger RT in temporal judgements when participants had to change mental viewpoints in both space and time (Tproj: m.d. = 184 ms, t = 5.67, p < 0.001 and Sproj: m.d. = 111 ms, t = 2.43, p < 0.05, respectively; Fig. 4C). Tproj were found to produce a larger RT increase than Sproj, but only as a trend (post hoc *t*-test: m.d. = 73 ms, z = 1.38, p = 0.085). Conversely, RT in spatial judgements were significantly increased by self-projection in time and in space (Tproj: m.d. = 79 ms, t = 3.69, p < 0.001 and Sproj: m.d. = 130 ms, t = 6.47, p < 0.001, respectively; Fig. 4C). This increase was significantly larger for Sproj than for Tproj (post hoc *t*-test: m.d. = 51 ms, z = 4.59, p < 0.001).

Similar profiles were found in ER_{DIST} models testing STREF effects (Table 2). Error rates in temporal judgments trials were significantly larger when self-projecting in time (Tproj: m.d. = 6.8, t = 8.13, p < 0.001) and marginally larger when self-projecting in space (Sproj: m.d. = 1.6, t = 1.84, p = 0.065) than when no self-projection was required (Fig. 4D). Increases in ER differed significantly between Tproj and Sproj (post hoc Wald test: m.d. = 5.2, z = −7.9, p < 0.001). A similar pattern was observed when participants performed spatial judgments: ERs were significantly increased by self-projection in space and in time (Sproj: m.d. = 7.3, t = 5.64, p < 0.001 and Tproj: m.d. = 2.6, t = 2.78, p < 0.01, respectively; Fig. 4D). This increase was significantly different between Tproj and Sproj (post hoc Wald test: m.d. = 4.4, z = −7.7, p < 0.001).

3.2.3. Relative DE remain dimension-specific

A significantly better fit of RT_{DIST} model was found when SD and TD effects were included (Table 2). Planned comparison revealed a significant decrease of MTT response times with increasing TD (t = −3.02, p < 0.005, Fig. 5A, left panel). Conversely, we observed a significant decrease of response times in MSN when SD increased (t = −2.82, p = 0.005, Fig. 5A, right panel). Crucially, only TD for MTT and SD for MSN gave rise to a symbolic distance effect as shown by significant TD:DIM and SD:DIM interactions (t = 2.42, p < 0.05 and t = −2, p < 0.05, respectively). As for error rates, a significantly better fit of ER-DIST model was found by including SD and TD effects (Table 2). We observed only a significant decrease of MSN response times when SD increased (t = −3.6, p < 0.005, Fig. 5B, right panel) and a non-significant trend for the decrease of MTT response times when TD increased.

3.2.4. Interactions between absolute DE and relative DE are dimension-specific

A triple interaction between spatial distance, reference and dimension (SD:STREF:DIM) significantly improved the RT_{DIST} model (Table 2), indicating that the interaction between spatial relative DE and self-projection in space only occurred for spatial judgements. As described earlier, spatial relative DE was observed for MSN, so that the more spatially distant the event from the imagined self-position, the faster the RT. Planned comparisons showed a qualitatively similar interaction as reported in Experiment 1 for ER (Fig. 3E, right panel): a significant increase of the slope of spatial relative DE was found when subjects performed spatial judgements while self-projected in space (Sproj) compared to the no self-projection condition (t = 3.9, p < 0.001, Supp. Fig. 1A). In error rate model ER_{DIST}, both SD:STREF:DIM and TD:STREF:DIM improved significantly the quality of the model. Both triple interactions demonstrated that the observed interaction between absolute and relative distance effects is dimension-specific. Again, a significant increase of the slope of spatial relative DE was found

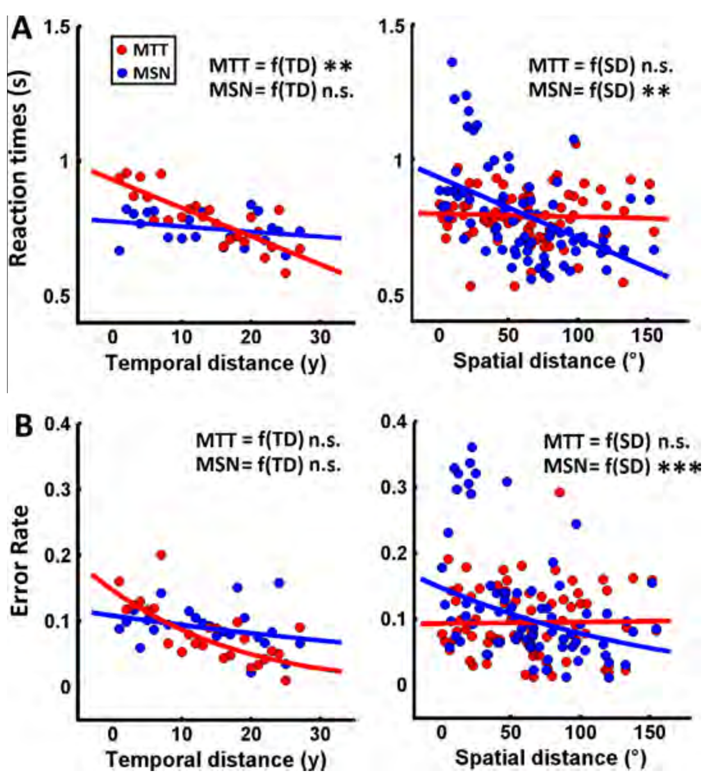


Fig. 5. Relative distance effects are dimension-specific. A. Dimension-specific relative distance effect of reaction times. As previously reported, RT of MTT decreased with the temporal distance separating the event from the temporal reference; similarly, RT of MSN decreased with the spatial distance separating the event from the spatial reference. B. Dimension-specific relative distance effect of error rates. ER of MTT showed a trend to decrease with the temporal distance separating the event from the temporal reference; ER of MSN decreased with the spatial distance separating the event from the spatial reference. ** p < 0.01; *** p < 0.001.

when subjects performed MSN while self-projected in time (Sproj) as compared to the no self-projection conditions ($t = -5.1$, $p < 0.001$, Supp. Fig. 1B). Similarly, the slope of the spatial relative DE significantly increased when subjects performed MTT while self-projected in time (Tproj) as compared to no self-projection conditions ($t = -3.1$, $p < 0.005$, Supp. Fig. 1B).

3.3. Discussion

Experiment 2 was designed to maximize potential space-time cross-dimension effects by ensuring that participants maintained both dimensions of a given reference in mind while alternating MTT and MSN.

First, we observed a switch cost effect, namely: switching from MTT to MSN increased RT as compared to staying in MTT and conversely, switching from MSN to MTT increased RT as compared to MSN. The switch cost was asymmetric and strongest when switching from MSN to MTT. This effect was confined to RT and did not extend to ER. We are confident that trivial sources of switch cost can be set aside (Monsell, 2003): a single set of events was used so the switch cost was not caused by different event occurrence probability across tasks. Moreover, the two tasks equally and simultaneously relied on memory retrieval. We tentatively interpret the switch cost as an effect of successively mapping temporal and spatial dimensions of events. As the switch cost did not impair performance (i.e. no switch cost was measured with ER), this effect was likely pre-decisional (Meiran, 1996). The asymmetric switch cost suggests that mapping temporal metrics may require additional cognitive processes compared to spatial metrics.

Second, absolute DE was replicated showing that intermixing MTT and MSN did not perturb self-projection in time or space. Moreover, we found a cross-dimensional DE indexed by an increase of RT and ER when self-projection was performed in the irrelevant dimension. Two possible interpretations for this space-time cross-dimension effect are: (i) a unique mental map or coordinate system is used for time and space representation so that any self-projection will necessarily occur in either dimensions, or (ii) a single map is used per dimension and the irrelevant map is actively suppressed during self-projection. The overall pattern of effects supports the latter hypothesis: relative DE and its interaction with self-projection were dimension-specific, suggesting that distance metrics computation was confined to a single dimension. Moreover, self-projecting in the irrelevant dimension impacted less the RT than self-projecting in the relevant dimension, consistent with the hypothesis of two different cognitive sources: active suppression of the irrelevant map and self-projection.

The fact that the question was presented before the event in Experiment 2 may have weakened the absolute DE observed when self-projection was performed in the irrelevant dimension as opposed to the relevant dimension. It was thus possible that the presentation of the event before the question would help preserve as strong an absolute DE across dimensions as within, thereby invalidating the need for dimension-selective maps and an active map suppression mechanism. This is what we tested in Experiment 3.

4. Experiment 3: Knowing the event before the dimension of the question preserves absolute and relative DE patterns

4.1. Materials and methods

4.1.1. Participants

13 subjects (8 males; mean age = 24.1 ± 7 years old), all right-handed with corrected-to-normal vision and no history of psychological disorders participated in the study. All participants lived in the Parisian region. The ethical protocols and compensations were identical to Experiment 1.

4.1.2. Stimuli and procedure

The experimental procedure was identical to the one used in Experiment 2 asides from one major and four minor parameter changes. The major change consisted in presenting the EVENT before the QUESTION during a given trial (Fig. 1A). The minor changes consisted in changing the number of trials per blocks (72), the reference presentation duration (5000 ms minimum followed by a self-paced start), the event and question slides durations (750 ms) and the display of the events (three words, mentioning the country of historical events for some events (cf. Supp. Table 1). These minor changes were due to specific design constrains dedicated to the subsequent analysis of the concurrently acquired magnetoencephalographic brain responses.

4.1.3. Statistical analysis

Distance effects were analyzed in the same way as Experiment 2. We used one linear mixed model for RT and one for ER. For each model, the four factors of interest (TD, SD, STREF and DIM) underwent AIC-based selection (Supp. Table 3) and planned comparison and post hoc p-values were derived from the final model.

4.2. Results

Adding a DIM factor significantly improved RT_{SWITCH} and RT_{DIST} models (Table 2). MTT took longer that MSN ($t = -2.7$, $p < 0.01$) and MSN was more error-prone that MTT ($t = 2.5$, $p = 0.01$).

4.2.1. Absolute DE capture space-time cross-dimension effect

First, a significantly better fit of RT_{DIST} model was found when including STREF effect (Table 2). Planned comparisons showed that RT in MTT were significantly longer when participants were self-projected in time (TPROJ: m.d. = 162 ms, $t = 11.8$, $p < 0.001$) and in space (SProj: m.d. = 78 ms, SProj, $t = 3.7$, $p < 0.001$) as compared to no self-projection (Fig. 6A). This increase was significantly higher for TProj than for SProj (post hoc *t*-test: m.d. = 65 ms, $z = 2.01$, $p = 0.044$). A similar pattern was found for MSN: RT were significantly longer when participants self-projected in time (TProj: m.d. = 102 ms, $t = 5.0$, $p < 0.001$) and in space (SProj: m.d. = 76 ms, $t = 5.1$, $p < 0.001$) (Fig. 6A). The observed increase in RT was significantly higher for SProj than for TProj (post hoc *t*-test: m.d. = 79 ms, $z = 4.19$, $p < 0.001$).

Similar profiles were found in ER_{DIST} model for STREF effect (Table 2). Participants produced significantly more errors for MTT when engaged in self-projection in time (TProj, mean error rate difference (m.d.) = 6.8, $t = 8.13$, $p < 0.001$) and marginally more errors for self-projection in space (m.d. = 1.6, SProj, $t = 1.84$, $p = 0.065$) (Fig. 6B). This increase differed significantly between TProj and SProj (m.d. = 5.2, $z = -7.9$, $p < 0.001$). A similar pattern was observed for MSN: significantly more errors were produced when engaged in self-projection in space (m.d. = 7, SProj, $t = 5.64$, $p < 0.001$) and in time (TProj: m.d. = 2.6, $t = 2.78$, $p < 0.01$) than when no self-projection took place (Fig. 6B). This increase differed significantly between TProj and SProj (m.d. = 4.4, $z = -7.7$, $p < 0.001$).

4.2.2. Relative distance effects remain mostly dimension-specific

A significantly better fit of RT model was found by including SD and TD effects in RT_{DIST} models (Table 2). For MTT, planned comparisons revealed a significant decrease of RT with TD ($t = -5.8$, $p < 0.001$, Fig. 6C). For MSN, RTs showed a significant decrease with SD ($t = -9.5$, $p < 0.001$, Fig. 6C). Surprisingly, a significant decrease of RT in MTT was also observed with SD ($t = -2.5$, $p < 0.05$). However, we are confident that this effect does not fundamentally alter

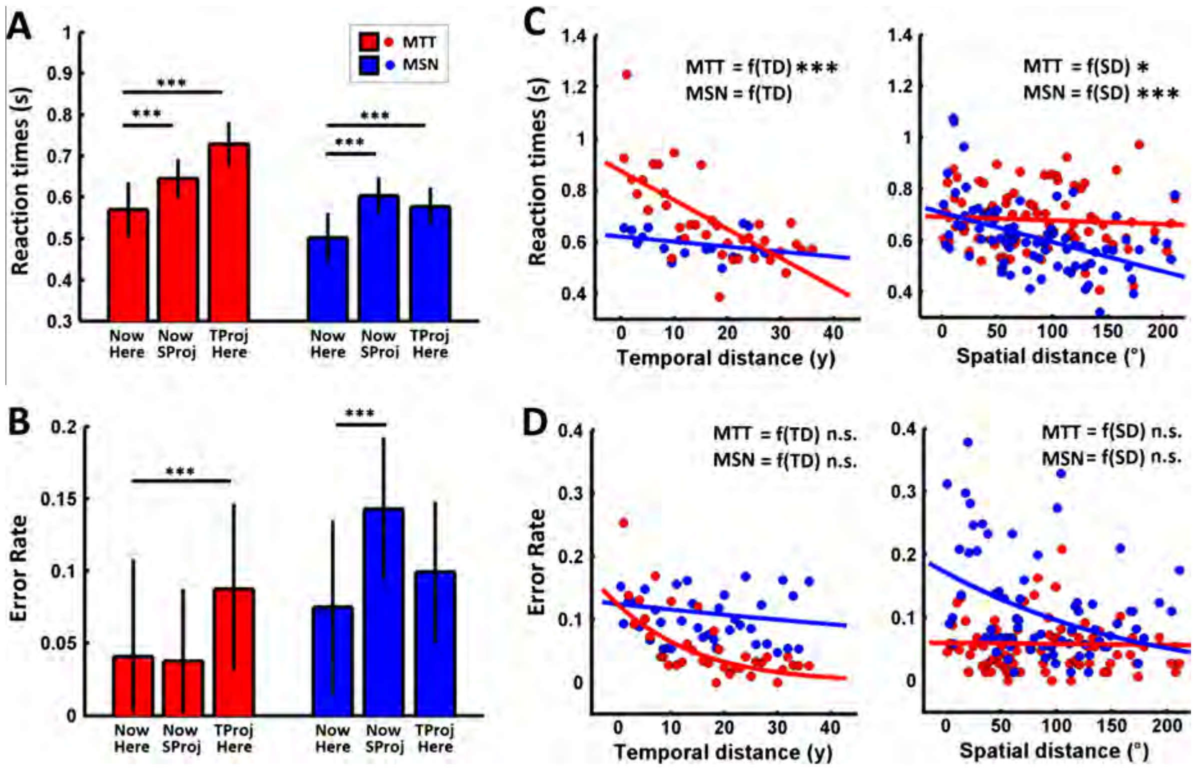


Fig. 6. Distance effects in Experiment 3. A. Cross-dimension absolute distance effects in RT: Self-projection in time (TProj) significantly increased RT for MTT (red) as compared to "Now Here" condition; self-projection in space (SProj) significantly increased RT for MSN (blue) as compared to the "Now Here" condition. Additionally, and like in Experiment 2, a dimensionless absolute DE was also observed, in which TProj increased RT for spatial judgements and SProj increased RT for temporal judgements as compared to the "Now Here" condition. B. Dimension-specific absolute DE of error rates: Self-projection in time (TProj) significantly increased ER for MTT (red) as compared to "Now Here" condition; self-projection in space (SProj) significantly increased RT for MSN (blue) as compared to the "Now Here" condition. C. Dimension-specific relative distance effect of reaction times. As previously reported, RT of temporal judgements decreased with the temporal distance separating the event from the temporal reference; similarly, RT of spatial judgements decreased with SD. Unexpectedly, we found a decrease of RT with SD for MTT. D. Dimension-specific relative distance effect of error rates. ER of temporal judgements showed a non-significant trend to decrease with TD; similarly, ER of spatial judgements showed a non-significant trend to decrease with SD. * $p < 0.05$; *** $p < 0.001$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the robustness the dimension-specificity evidenced in Experiment 1 and 2. This is further discussed in Section 4.3.

Consistent with results observed in Experiment 2, we found a relative DE for MTT and MSN which displayed significant temporal and spatial distances by dimension interactions (TD:DIM and SD: DIM interactions, $t = 3.6$ and $t = -6.9$, $p < 0.001$ and $p < 0.001$, respectively).

A higher variability in error rates was found in Experiment 3 as compared to Experiment 1 and 2. Hence, although some trends for a decrease of ER with temporal distance in MTT and spatial distance in MSN were seen (Fig. 6D), no significant effects were found for error rates.

4.2.3. Interactions between absolute and relative DE remain dimension-specific

A triple interaction between temporal distance, reference and dimension (TD:STREF:DIM) was found to significantly improve the RT_{DIST} model (Table 2), indicating that the interaction between temporal relative DE and self-projection in time happened only for MTT. In this experiment, planned comparisons revealed a significantly stronger decrease of RT with TD when participants were self-projected in time as compared to no self-projection ("TProj Here" *vs.* "Now Here", $t = 2.9$, $p < 0.005$, Suppl. Fig. 2A).

In error rate models ER-DIST, both STREF:TD:DIM and STREF: SD:DIM interactions were found to significantly improve the ER-DIST models (Table 2). These two interactions demonstrated that the observed interactions between absolute and relative DE are dimension-specific. Similar to Experiment 2, planned comparisons revealed significantly stronger decreases of ER with TD when participants performed MTT while self-projected in time as compared to no self-projection ("TProj Here" *vs.* "Now Here", $t = -5.7$, $p < 0.001$, Supp. Fig. 2B). Conversely, ER decreased with SD more strongly when MSN were performed while self-projected in space as compared to in the absence of self-projection ("Now SProj" *vs.* "Now Here", $t = -2.9$, $p < 0.005$, Supp. Fig. 2B).

4.3. Discussion

In Experiment 3, presenting the event before the question did not alter the pattern of absolute DE observed in Experiment 2 and in particular, we found the same cross-dimension effect. In support of the active suppression hypothesis proposed in Experiment 2, this effect across dimensions remained smaller than the absolute DE and again, we observed a dimension-specific interaction between absolute and relative DE: relative DE was increased in the case of self-projection in the dimension being judged.

We replicate Experiment 1 and 2 with respect to the presence of a dimension-specific relative DE in MSN but not fully in MTT: the spatial distance significantly affected the reactions times so that the larger the spatial distance, the smaller the reaction times. The presentation of the event before the question in Experiment 3 induced more errors overall in both MTT and MSN. This suggests that the uncertainty on the dimension to be judged rendered the task more difficult for participants. Additionally, in MTT reaction times increased and error rates decreased as compared to MSN. MTT thus appeared to be more difficult overall than MSN. We suggest that one possible explanation for the significant cross-dimension effect between spatial distance and reaction times in MTT (but not temporal distance and reaction times in MSN) is that by default, participants may have been biased to engage in a spatial judgment before being prompted with the question. This would account for the differences of reaction times between MTT and MSN (the latter being overall faster) but also why we do not observe this cross-dimension effect in Experiment 1 and 2. In other words, this bias would be essentially due to the uncertainty triggered by the reordering of event and question presentation in the trial.

5. General discussion

Using three experiments, we tested the hypothesis that Mental Time Travel (MTT) and Mental Space Navigation (MSN) shared cognitive operations. Shifting mental perspectives in the temporal or spatial dimensions in the absence of sensorimotor cues was hypothesized to entail the establishment of cognitive maps and the computation of distances *as per* the ordinality judgments required by the task. To test this hypothesis, we emitted alternative predictions regarding the presence or absence of distance effects (DE) in space and time. *Absolute* and *relative* DE were replicated in the simplest version of the design (Experiment 1) and reproduced in more complex versions in which MTT and MSN were intermixed, validating the hypothesis of common cognitive operations as well as in-depth probing of cross-dimension effects. To summarize, absolute DE suggests the existence of self-projection in both time and space while relative DE suggests the mental mapping of ordinal relations between the self and mental events. Our major findings reveal novel space-time cross-dimensions DE: we report robust cross-dimension effects for absolute DE but not for relative DE, suggesting that while self-projection may use similar map transformations, the computation of spatial and temporal metrics remain dimension-specific.

5.1. Absolute distance effects: self-projection as conversion of egocentric maps

Absolute DE capture the fact that ordinal judgements were slower and less accurate for imagined viewpoints than for factual "here and now", thus suggesting that changing mental viewpoint comes at a cost. In MTT, absolute DE has been interpreted as self-projection or the relocation of the self on a fixed coordinate system called the Mental Time Line (Arzy, Adi-Japha et al., 2009; Bonato et al., 2012). According to this view, absolute DE would result from the difficulty to access events located far away on the Mental Time Line (MTL) (Arzy, Adi-Japha et al., 2009). The MTL hypothesis provides an intuitive scheme to think about the mental mapping of ordinal relations in time but may also present some issues.

Specifically, it could be argued that when the repositioning of the self on the MTL has taken place (in the beginning of an experimental block), no additional self-positioning should be needed for the following trial. For instance, if self-projection nine years ago was made at the start of the block, all following trials should now be within the same "nine-years ago" reference without the need to go back to the "now" reference. The observed absolute DE in Experiment 1 suggests that self-projection operated on a single-trial basis therefore interfering with the retrieval of the event from memory – i.e. likely at the presentation of the historical event. In other words, a default temporal reference is likely used during retrieval and an active remapping may translate the default retrieval coordinate system on the new projected self-position. A similar interpretation holds for the absolute spatial DE found in MSN, which would be consistent with spatial updating studies proposing that spatial events are recalled with respect to an intrinsic "here" reference frame (Easton & Sholl, 1995; Mou & Mcnamara, 2002).

Under this operational hypothesis, absolute DE would result from the cost of remapping the event set in a new egocentric referential centered on the imagined self, whether in time or in space. Such ability may be specific to humans as it fits well with the *www memory criterion* (what/where/when) and would underlie a more general ability for Mental Travel (Tulving & Donaldson, 1972; Suddendorf et al., 2009; Zacks & Radvansky, 2014). It is also intuitive that the www dimensions of events in memory should be immune to changes therefore needing a post-retrieval contextualization.

As absolute DE was observed in MTT and in MSN, the transient setup of coordinate systems for self-projection and psychological distance computations may be a domain-general capacity. For instance, recent theories have highlighted the importance of psychological distances to self in social sciences (Liberman & Trope, 2014) and similar parietal brain regions have been shown to be implicated in self-projection along various dimensions including time, space and social domains (Buckner & Carroll, 2007; Parkinson, Liu, & Wheatley, 2014; Peer, Salomon, Goldberg, Blanke, & Arzy, 2015).

Taken together, self-projection may involve the conversion of a cognitive map from the actual position of the self in time and space (the "now and here", by default) to the imagined self-location along the dimension required by task. This hypothesis specifically predicts that the larger the distance the mental reference or viewpoint is from the here and now, the more pronounced the absolute DE.

5.2. Relative distance effects refers to self-position

Relative DE can be considered an instance of the classical symbolic distance effect, which reflects the ordinal comparison between two mental referents (Moyer & Bayer, 1976).

There are specific issues for the mapping of ordinal relationships in time, i.e. temporal order, within the postulate of a MTL. In the well-studied mapping of numerosity, number is ordered and indexed along a culturally defined spatialized mental linear map referred to as the Mental Number Line (Dehaene, 2003; Dehaene, Bossini, & Giraux, 1993; Feigenson et al., 2004). Analogous to the Mental Number Line (MNL), the MTL has been hypothesized to serve as the mental referential for MTT (Arzy, Adi-Japha et al., 2009; Bonato et al., 2012). In this framework, the location of two events on the MTL would thus index the distance separating two events. This hypothesis also implies that the MTL is an allocentric - hence, non-egocentric - representational system in which the representation of self-position has no special status compared to any other mental events. One key feature of the MTL is that it provides a left-to-right arrangement conferring its past-future direction to time (Bonato et al., 2012). On the MNL, estimating a numerical difference is directly derived from each number magnitude but the relationship between the location of an event in the hypothesized MTL and the projected temporal self-location may be trickier: specifically, the difference of magnitude between two events is insufficient to derive temporal order unless an origin to the referential is posited. This question was previously raised in the context of spatial representation and our study raises the question of an origin to such referential system due to the self-related ordinality judgement participants had to perform. The hypothesis of an egocentric mapping would resolve this issue. It is also noteworthy that in the spatial domain, the finding of relative DE is informative on the mental operations used to perform the MSN task: if participants were using mental imagery in an allocentric map to solve the task, RT would increase with distance when moving from one location to another one (Shepard & Metzler, 1971; Kosslyn et al., 1978). Symbolic DE shows the reverse pattern.

The observation that task difficulty increases when events are closer to the mental viewpoint suggests that the origin of the referential may be flexible for tasks requiring self-projection, and that the origin of the referential is likely egocentric – whether egocentricity pertains to the physical self (here, now) or the projected self.

Additionally, we observed an interaction between distance and self-projection which is strongly consistent with the hypothesis that relative DE are bound to egocentric maps in these tasks. The precise origin of such interaction remains unclear. Distortions of psychological distances have been reported when reference points are used (Tversky, 1992), and subjective stretching of spatial distances near an explicit spatial reference reported when using distance estimation tasks (Birnbaum & Mellers, 1978; Holyoak & Mah, 1982). Such distortions may be due to familiarity: Holyoak and Mah (1982) hypothesized that distortions of spatial representation could reflect the tuning of spatial maps biased towards the representation of landmarks closest to the actual place a person lives in. These early reports are consistent with our observation of increased error rates for events spatially close to unfamiliar locations (sp. Cayenne and Dubaï). By analogy, in the time dimension, participants may be more familiar with events belonging to their current temporal vicinity than with events far in the past or in the future (Rubin & Schulkind, 1997; Spreng & Levine, 2006) thereby affecting the granularity of mental representations.

As comparable relative DE was found in time and space with similar interaction patterns, the initial encoding format may not be critical for the mental representation used here. In the number processing domain, given the same distance, the comparison of two large numbers has been shown to take longer than between two smaller numbers (Dehaene, 1992; Parkman, 1971; Gallistel & Gelman, 1992). One possibility is that this effect is a general property of abstract representations generalizing for any computations of psychological distances operating on discrete mental events. In other words, our findings converge with the general notion that internal mapping of information follows the Weber–Fechner's law although the logarithmic or scalar nature of such mapping remains debated (Dehaene, 2001, 2003; Dehaene & Brannon, 2011; Gallistel, 2011).

5.3. Active suppression hypothesis: when time and space compete

We report a novel finding of space-time cross-dimension absolute DE during self-projection (Experiment 2; replicated in Experiment 3): participants' performance was impaired when self-projection occurred in one dimension (e.g. time) and their judgment had to be made in the other dimension (e.g. MSN). Although such cross-dimension absolute DE was predicted from the unique spatiotemporal map hypothesis (Fig. 1E), significant differences were found between the observed effects and the predicted ones.

First, the cross-dimension absolute DE was significantly reduced compared to the single-dimension absolute DE. Second, we found strong cross-dimension DE for RT but weak effects for ER. From these observations, we hypothesized an "active suppression" mechanism in which actively suppressing the map of the irrelevant dimension (e.g. temporal map) may contribute to increasing the RT (e.g. of a spatial judgment). The need of an active suppression mechanism would originate from an underlying competition between temporal and spatial maps and marginal effects in ER may originate from actual failures to suppress the irrelevant map which would be used to perform the task. Consistent with the active suppression hypothesis, relative DE as well as its interaction with self-projection were confined to the dimension relevant to the task. This is supporting the idea of map-selectivity for the computation of distance metrics in space and time.

The underlying competition may concern allo-to-egocentric map conversion. When there is incongruence between the dimension of self-projection and the dimension of the judgement, temporal and spatial maps compete for egocentric remapping. This would be particularly relevant when there is ambiguity regarding the dimension of interest; once ambiguity has been resolved (i.e. at the presentation of the question), the irrelevant map can be suppressed thereby enabling access to egocentric mapping of the relevant dimension. The cost of switching dimensions reported in Experiment 2 could be interpreted as the time needed to suppress the irrelevant map. In addition to the cross-dimension effects in absolute DE, two asymmetrical effects between space and time were found when uncertainty was introduced in the experimental design. In Experiment 2, when the dimension of interest could change from one trial to the next, the switch cost was smaller when switching from space to time than from time to space. In Experiment 3, the question was provided at the end of the trial leaving participants uncertain as to the required dimension and judgments performed in MSN were found to be faster and less accurate than in MTT. Thus, these two effects suggest that under uncertainty, the spatial dimension may be defaulted over the time one.

6. Conclusions

Altogether, our study shows that distance effects in Mental Time Travel and Mental Space Navigation could be consistently explained by similar cognitive mapping principles, namely: egocentric mapping and coordinate system conversion. Egocentric mapping provides an adapted representation for relative judgements in time or in space, while self-projection allows maintaining egocentricity of the map when adopting a viewpoint differing from the "here and now". Our interpretation emphasizes the importance of the representation of self as the point of origin in cognitive maps for time and space, even when the self is an imaginary one.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.cognition.2016.05.015.

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