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Neural bases of the modulation of the Mental Time Travel ability.

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Contents

Abstract

Mental Time Travel (MTT) represents the ability to cognitively move through time, envisioning oneself at different temporal moments — Present, Past, or Future — while ordering events along the Mental Time Line (MTL). Several studies demonstrated that, in the Western culture, Time is cognitively represented along a horizontal line which is spatially oriented from left to right. This spatial representation is configured from an egocentric perspective, defining the directionality of temporal flow from the Past, located on the left portion of the MTL, towards the Future, represented on the right.

The ability to mentally navigate the spatial representation of Time can be modulated by the spatial attention deviation induced by prismatic adaptation and can be affected by the objective temporal distance of the events.

However, the effects of temporal distance as perceived by the subject have never been investigated, and it remains unclear how such manipulations modulate the activity of the brain network subtending MTT. Therefore, the purpose of this doctoral thesis is to explore the neural correlates underlying the modulation of MTT by means of two functional Magnetic Resonance (fMRI) studies.

In the first experiment, thirty-seven healthy volunteers underwent an MTT task using a single-event protocol, both before and after prismatic adaptation with spatial attention deviation towards the left, corresponding to the representation of the past. Inside the MRI scanner, participants were asked to mentally project themselves (Self-Projections) into either the Present, or the Past (10 years ago), or the Future (in 10 years), and judge whether a series of events were either past or future (Self-Reference), relatively to the temporal Self Projection. Results showed improved performance for projection and reference to the past, following the spatial attention deviation to the left induced by the prismatic adaptation; furthermore, we revealed that this improvement was mediated by the modulation of activity in the bilateral inferior parietal lobule and decreased activity in the left superior frontal gyrus. Spatial attention deviation during the task was mediated by bilateral activation of the superior temporal gyrus.

The effect of perceived temporal distance of events was studied in the second experiment. Thirty-three of the participants who took part in the first experiment, subsequently provided an estimate of the perceived distance, relative to the temporal projection, for each event presented during the fMRI task. Parametric analyses of the BOLD signal using these estimates as factors allowed to identify the brain regions where activity during MTT is modulated by the perceived temporal distance. Results showed that events, both past and future, perceived as close, affect the Mental Time Travel performance. Furthermore, this effect involves the activity of angular gyrus bilaterally, retrosplenial cortex, temporo-parietal regions, and middle and superior frontal gyri. Therefore, these regions may mediate the spatial representation of time and the subjectively perceived temporal distance of events. Additionally, perceived close future events recruit the left parahippocampal and lingual gyri and the right cerebellum, which might be implicated in this task for their role in imaginative functions.

In summary, the present studies have confirmed that time and space share a similar cognitive representation (spatially defined) and have identified the brain networks responsible for modulating Mental Time Travel in humans.

Introduction

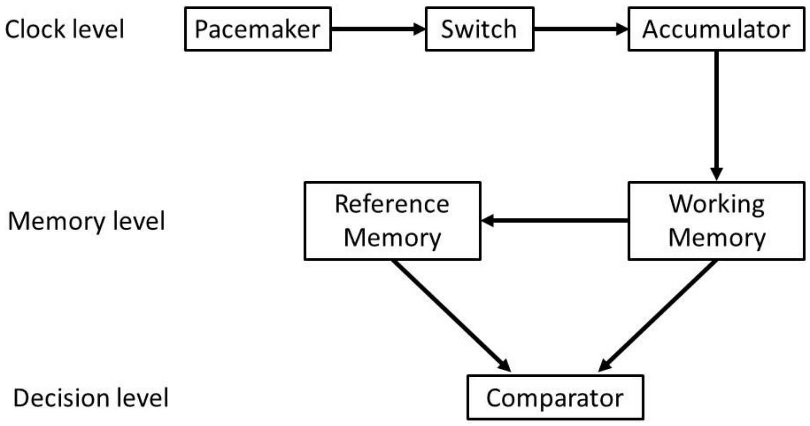
1. Time processing

1.1 Cognitive models of temporal processing

The study of Time has widely fascinated philosophers and researchers since Ancient Greece. However, the first attempt to measure the subjective time perception was proposed in 1927 by François (Wearden, 2019) and in 1935 by Hoagland; these Authors established a correlation between the ability to subjectively perceive the passing of time and physiological variables, such as body temperature. This correlation suggested the existence of an internal mechanism for time processing, similar to an internal Clock, which may regulate cognitive and physiological time. The conceptualization of an internal Clock enabled Triesman (1963) to articulate the first cognitive model of temporal processing, which was revisited by Gibbon and colleagues (1984), enriching it with experimental evidence and cognitive interpretations. The Scalar Expectancy Theory (SET) model is grounded on the Human Information Processing theory and stands as the most widely accepted model of time cognition. According to the SET, time perception follows the general principles which rule the perception in other dimensions. Specifically, classical Subjective Psychophysics claims that the perception of dimensions such as brightness, loudness, motion detection, and time, follow Weber's law, implying that the discrimination between two stimuli increases linearly with their intensity. The scalar property, derived from this law, gives SET its name, meaning that the variability of judgments around the temporal interval "t" remains constant as "t" varies. Hence, time perception represents a function that aligns with the psychophysics of general perception. This reinforces the hypothesis of an internal psycho-physiological system specific for time.

The SET system is grounded on the principal level, the Clock, which comprises a Pacemaker and an Accumulator. The Pacemaker produces "ticks" or "pulses", which are gated, with a constant period, by a Switch to an Accumulator, which collects them. To measure the duration of a stimulus, the

Switch is closed by the stimulus onset, allowing pulses to flow towards the Accumulator, and when the stimulus period finishes, the Switch re-opens, and interrupts the connection between the Pacemaker and the Accumulator. Accordingly, the Accumulator holds a number of pulses corresponding to the stimulus duration, that is, a raw representation of stimulus time, which will pass through cognitive processing in the following SET levels. This raw representation is then transferred from the Accumulator to a short-term memory or working memory system specific for time processing at the memory level. The memory level includes the Reference Memory, that is, a long-term memory storage, which contains relevant times, such as standard durations presented in temporal tasks. Finally, at the decision level, a standard drawn from the Reference Memory is compared to the contents of working memory by the Comparator.



A representation of the Scalar Expectancy Theory (SET) system adapted from Gibbon et al. (1984).

The SET is supported by abundant evidence and has been demonstrated in various subjects, including animals (Church and Guilhardi, 2005; Church and DeLuty, 1977), human adults (Pouthas, 2005; Rammsayer, 1997), and children (Droit-Volet and Wearden, 2001; Droit-Volet and Rattat, 2006).

The SET has been validated by means of the “time duration” experimental paradigm. In duration tasks with humans, repeated presentations of two standard stimulus durations (short and long) are provided to participants, who subsequently judge whether probe durations (short, long, and intermediate stimuli) are similar to either the short or the long standard. This paradigm ensures that probe durations are compared to standard durations stored in the Reference Memory before the decision process leads to a behavioural response.

An alternative approach is the time bisection task, which requires participants to calculate a bisection point. This point corresponds to the subjective midpoint of the temporal duration, resulting in 50% of "long" responses. Differently from the short and long intervals, the objective midpoint of the temporal duration is not repeatedly presented in the initial phase of the task, in order to avoid its representation in the Reference Memory. Consequently, the bisection point offers a measure of the subjective mental representation of that duration, which can be compared to the objective one or experimentally manipulated.

Although the initial representation of stimulus duration is formed in the first level of the system (specifically, in the Accumulator), additional cognitive processes are required to generate timing behaviour. Therefore, according to SET, when a participant is submitted to a timing task, the observed behaviour must be regarded as reflecting underlying Clock processes only indirectly. Different experimental conditions and participant groups may yield different behaviours not due to differences in "raw" timing (i.e., Clock) processes but to differences in memory and decision mechanisms instead. This subtends the importance of the integrity of cognitive components (Memory and Decision-making mechanisms) in time processing and demonstrates how SET is an intricate multi-process model. Therefore, time processing is recognized nowadays as a fundamental topic in Cognitive Neuroscience, and it has given rise to a line of research on the cognitive processes involved, resulting in several alternative models, such as the State-Dependent Networks Model (SDNs; Karmakar and Buonomano, 2007; Buonomano and Merzenich, 1995; Buonomano, 2000) or the Multiple Time-Scale theory (MTS; Staddon et al., 1999). Despite the other theoretical models formulated to elucidate time processing functions, the model that has garnered the most consensus and empirical evidence is the SET.

1.2 Neural bases of temporal processing

Over the years, a great number of studies have been conducted to investigate the neural underpinnings of time perception in accordance with the Scalar Expectancy Theory (SET) model (Harrington et al., 1998; Rao et al., 2001; Smith et al., 2003; Ivry and Spencer, 2004; Hinton and Meck, 2004; Jech et al., 2005; Koch et al., 2004; Koch et al., 2008; Bueti et al., 2008). The identification of a widespread brain circuit consisting in several cortical and subcortical regions, with each area corresponding to a specific component of the model, further confirms the complexity of both time processing and of the cognitive model itself.

Following the SET model structure, the Clock level, and in particular the Pacemaker functions, has been located in the basal ganglia, specifically in the dopaminergic system. In rats it has been, indeed, demonstrated that the striatum's activity and its afferent projections from the substantia nigra pars compacta (SNPC) are fundamental for temporal production and estimation tasks (Dallal and Meck, 1993; Clarke et al., 1997; Matell et al., 2000). Rats with lesions in the striatum or selective dopaminergic lesions in the SNPC exhibit impairments in adjusting their responses relative to the elapsed time. Pharmacological data in rats confirm the involvement of the basal ganglia in timing processes. The systemic administration of dopaminergic drugs (Meck, 1983, 1996; Matell and King, 1997; Matell et al., 2004), and their direct administration into the anterior part of the striatum (Neil and Herndon, 1978) affect the speed of interval timing processes. Notably, dopaminergic agonists (e.g., methamphetamine, cocaine) lead to faster responses, i.e., to the perception of accelerated time speed as compared to control conditions (Matell and King, 1997), while dopaminergic antagonists (e.g., haloperidol) lead to slower responses, due to the perception of reduced time velocity (Neil and Herndon, 1978). The impact of dopaminergic activity on time processing is also corroborated by studies on patients affected by Parkinson's disease (PD), who present basal ganglia and dopaminergic dysfunctions. Indeed, patients with PD tend to underestimate interval durations compared to healthy controls (Pastor et al., 1992), and dopaminergic medications (levodopa) reduce these errors. In addition, Koch et al. (2004) showed that a sub-thalamic electrode implantation, stimulating the striatal system, also mitigates time perception alterations in PD patients, reproducing the effects of dopaminergic agonists. This further proves the involvement of the basal ganglia in the Clock level functions, which is indeed considered the low-level component of the SET model. Recent studies also reported that PD's patients are impaired not only in the Clock functions related to the altered time velocity assessment, but also in cognitive dysfunction of time processing. Notably, Koch and colleagues (2008) demonstrated that PD patients are impaired in time tasks involving intervals in the range of seconds (and not milliseconds), which are usually related to the cognitively controlled time. In particular, these patients showed time estimation deficiency when different time intervals were tested in separate sessions, thus requiring patients to recall previously learned durations. This suggests that PD patients’ impairments are related to cognitive processes like memory and attention. Moreover, this cognitive component of time processing in PD patients highlights the link between the Internal Clock and other cognitive components of the SET model. While basal ganglia facilitate the counting time low-level function, the interaction with other cortical areas is necessary to implement time behaviour.

The supplementary motor area (SMA), usually a key region of the motor system, seems to be involved in cognitive temporal processing, too. The SMA indeed receives inputs from the basal ganglia and plays a pivotal role in motor timing (Lang et al. 1990). A recent review of the literature proposed that SMA plays a crucial role in sequence processing, integrating sequential elements into higher-order representations in different domains, including motor, temporal, spatial, numerical, linguistic, and working memory processing (Cona and Semenza, 2017). Specifically, in the temporal domain, the role of SMA could be ascribed to the Accumulator functions, including accumulating temporal pulses, and shaping the initial representation of continuous time intervals.

The role of dorsolateral prefrontal cortex (DLPFC), specifically in the right hemisphere, is well-established in time perception as related to the memory level of the SET model, in particular to the working memory functions, integrating information across delays and supporting temporal organisation of behaviours (Haque et al., 2021). Lesions studies confirmed the role of right DLPFC in working memory in time. Koch and colleagues (2002) reported a right DLPFC damaged patient, who showed a tendency to underestimate event durations, judging them shorter than they really were, and difficulties in estimating elapsed time since the beginning of events. The Authors interpreted it as evidence of the role of right DLPFC in monitoring the accumulation of pulses in the internal Clock during the interval presentation. In fact, if this accumulation process is impaired, some pulses may be missed, and accordingly a smaller number of pulses is accumulated, thus the interval is underestimated. As a support, applying repetitive transcranial magnetic stimulation (r-TMS) on the right DLPFC induces underestimation of time intervals (Koch et al., 2003). This result emphasises the role of this region in maintaining active representations of time intervals through working memory functions during the temporal encoding phase (Koch et al., 2003), thus tracking the passage of time.

The role of the medial temporal lobe (MTL) in episodic memory has been widely investigated, thanks to the famous patient H.M., who underwent a bilateral medial temporal lobectomy resulting in a complete memory loss (Squire, 2009). In the time duration domain, it has been proposed that MTL might be engaged at the memory level, serving as the long-term Reference Memory store for time events in the SET model. H.M. was indeed impaired in time reproduction tasks, showing a systematic tendency to underestimating durations longer than 20 seconds, which was interpreted as a failure in encoding or retrieving the task demands (Eisler and Eisler, 2001). Anatomical projections from the MTL to dorsal striatum regions involved in interval timing further support this proposition.

Recent emphasis has been placed on the right parietal cortex in time perception. More specifically, its pivotal role has been identified in interfacing sensor and motor processes in time reproduction tasks. A study using fMRI (Bueti et al. 2008) during time estimation and reproduction tasks suggest that the right inferior parietal cortex (right IPC) is crucial in time reproduction tasks, but it is not involved in estimation tasks. Thus, the Authors proposed that right IPC is engaged in linking sensory and motor processing in time reproduction tasks. From the SET model perspective, this area could mediate temporal processing from the central Clock to the peripheral motor effectors, facilitating the representation of time intervals essential for action. Since the link between action, timing and space is crucial to accurately act in the environment, right IPC represents the common ground for action-directed representation not only in time, but also in space (Walsh et al., 2003; Bueti and Walsh, 2009). Namely, the representation of time intervals seems to be spatially encoded on a line, called Mental Time Line (MTL), with ascending order from left to right, that is, intervals with shorter absolute duration are represented to the left of intervals with longer absolute duration, and right IPC activated during the discrimination of different temporal intervals, showing its involvement in the spatially organised metric of time intervals (Lewis and Miall, 2003a; Vicario et al., 2007, 2008; Oliveri et al., 2009a,b; Frassinetti et al., 2009). In addition, neuropsychological studies showed the impairment of both time and space cognition specifically in right parietal patients (Critchley 1953; Basso et al. 1996; Danckert et al. 2007) In particular, these patients presented time deficits with a significant tendency to underestimate the real time, whereas patients with left lesions were not impaired in time processing (Magnani et al. 2011).

Thus, in the SET model, the right parietal cortex might represent the neural substrate of the Comparator level, where time intervals are spatially represented and compared in order to produce a time response.

2. Mental Time Travel

2.1 Theoretical frameworks of the Mental Time Travel ability

Mentally travelling in time (MTT) has been defined as the human cognitive ability to re-experience past events and imagine future scenarios (Tulving, 1985). MTT is a highly complex capability, since it consists in disengaging from the current temporal location and in envisioning past or future episodes. It also enables to "focus attention internally" and intentionally remember specific past episodes or simulate possible future scenarios (Suddendorf and Corballis, 1997, 2007). Travelling towards the past relies on episodic autobiographical memory and the projection towards the future implies episodic future thinking (Dafni-Merom & Arzy, 2020). Namely, episodic autobiographical memory consists of the capacity to retrieve past events, personally experienced in specific places at specific time moments, being able to refer to "what", "where" and "when" they took place (Tulving, 1985). On the other hand, episodic future thinking is the ability to envision possible future scenarios and experiences, engaging mental imagery (D'Argembeau and Mathy, 2011), with the aim to reach goals, to solve problems and to make adaptive decisions (Atance and O'Neill, 2001; Szpunar, 2010). Thus, episodic autobiographical memory and episodic future thinking are linked by an evolutionary aim: remembering past events is useful to plan future actions in order to avoid past mistakes and to take into account past outcomes to make future decisions, and interact with others (Schacter and Addis, 2007; Suddendorf and Corballis, 2007).

In addition, the ability to mentally travel in time is intrinsically characterised by the autonoetic consciousness, that is, the self-knowing consciousness which allows us to understand the continuity and consistency of the self in the past, the present and the future (Tulving, 1985). Indeed, "*There can be no travel without a traveller*" (Tulving, 2005), which means that it is the human self which travels to the past or the future, constructing scenarios as based on episodic and semantic memory (Cheng et al. 2016; Szpunar et al. 2007).

Several theories proposed interpretative frameworks about MTT, focusing on different aspects. In the following paragraphs these MTT theories will be presented.

Constructive episodic simulation theory

The constructive episodic simulation theory (Addis, 2018) claims that remembering a fact and predicting possible events are based on similar constructive processes, where the person who is creating a memory/prevision assembles different kinds of features, such as people, emotions, objects in a specific spatio-temporal context (Addis, 2018; Schacter and Addis, 2007). This constructive nature makes this process highly flexible and adaptive and corroborates the hypothesis that the construction of future events relies on recombining elements from past happenings (Schacter and Addis, 2007). This is the advantageous feature of prospection since it allows us to avoid mistakes and make decisions, being aware of previous outcomes of our actions (Suddendorf and Corballis, 2007). In this respect, a well-known task is the "Crovitz cueing" procedure (Crovitz and Schiffman, 1974), which consists in presenting a word as a cue and in asking participants to provide as many details as possible. This procedure is classically used to re-experience a past event, but also to imagine a future one (D'Argembeau & Van Der Linden, 2004; Addis et al., 2007). Alternatively, the "autobiographical interview" procedure by Levine et al. (2002) employs a comprehensive and dependable scoring system to distinguish between internal (episodic) and external (non-episodic) details in transcribed protocols. The internal composite focuses on components of episodic memory, while external details are more diverse, aiming to encompass various non-episodic expressions such as general semantics, various types of personal semantic details, metacognitive statements, repetitions, and information about off-topic events. The aim of both tasks is to reconstruct the combining process which leads to the mental temporal journey, counting the details provided in participants' reports. However, the reconstruction of these events could come at a cost in possible inaccurate reconstructions of events (Schacter et al., 2018).

Scene construction theory

The scene construction theory (Hassabis & Maguire, 2007; Mullally & Maguire, 2014) focuses, instead, on the coherence of the spatial context per se, pointing out the role of scene-related processes in different cognitive functions, from MTT to navigation and perspective taking, as well as in episodic memory and in imagination of possible scenarios. Thus, scene construction consists of the process of mentally generating and maintaining a complex and coherent scene or event, by retrieving and integrating relevant semantic and sensory components from different modalities to a coherent spatial context (Hassabis & Maguire, 2007; Mullally & Maguire, 2014). According to this theory, the scene construction process, rather than the temporal context, represents the foundation of the episodic memories and of the imagined future experiences. It was hypothesised that in order to imagine the future it is necessary to transfer the self in time (Atance and O'Neill, 2001); however, Hassabis and Maguire (2007) argued that individuals can also imagine novel fictitious scenarios even if they are neither temporal nor self-relevant. Namely, these Authors (2007) hypothesised a crucial role of hippocampus in scene construction, because this structure allows the processing of spatial information and binds together elements useful to construct the imagined complex scene.

Self-Projection and Self-Reference

The concept of Self-Projection comprises the ability to mentally travel in time, and it goes further encompassing other forms of simulation, such as perspective taking or mental navigation (Buckner and Carroll, 2007). Indeed, Self-Projection is the capacity to shift perspective from the immediate environment to alternative scenarios, hence in MTT it consists in changing the viewpoint from the "here and now" to different moments of subjective time (Buckner and Carroll, 2007). Similarly, to previous theories, Buckner and Carroll (2007) proposed that Self-Projection depends on memory systems, starting from past episodes to represent alternative experiences. However, the main focus of this theory relies on the ability to project ourselves in different times (now vs then), places (here vs there) and personal or non-personal perspectives (self vs other).

A more chronometrical approach to the investigation of Self-Projection in time has been taken with the aim to disentangle the basic components of MTT (Anelli et al. 2016a, 2016b, 2018; Arzy et al. 2008, 2009a, 2009b, Gauthier and van Wassenhove 2016a, 2016b). A specific task has been conceived, the MTT task (Arzy et al. 2008), in which participants are asked to mentally project, that is, to imagine, themselves to three self-locations in time (10 years ago in the Past, now in the Present, and 10 years from now in the Future). Starting from one of these temporal moments, participants judged whether different events had already happened (relative past events) or had yet to happen (relative future events). This allowed the Authors to distinguish between the Self-Projection component of MTT, that is, the imagination of the self in different self-locations in time, and the Self-Reference component, which is the relation between the adopted temporal location and the experienced event (Arzy et al. 2008, 2009a). Indeed, at behavioural level participants were slower and less accurate when projecting to the Past and to the Future, as compared to the Present. This result suggested that Self-Projection requires a re-mapping of the egocentric point of view, in order to reconstruct the temporal context (Arzy et al., 2008, 2009b; Gauthier & van Wassenhove, 2016a). On the other hand, participants were faster when responding to relative future events as compared to relative past events, as if MTT were mainly a future oriented process (Arzy et al. 2008, 2009a).

2.2 Neural bases of Mental Time Travel

The previously mentioned theories hypothesised similar processes underlying the mental travel towards the Past and the Future. Several studies have investigated the neural bases underlying the various theoretical approaches just discussed, identifying similar neural correlates subtending the abilities of remembering the Past and of envisioning the Future. This widespread network has been recently called the “simulation system” (Addis, 2020). On the other hand, some studies also shed light on different subsystems mediating specifically the past or the future MTT, related to the recruitment of specific cognitive functions selectively required to mentally travel to different temporal moments. Functional Magnetic Resonance Imaging (fMRI) studies conducted within the framework of the constructive episodic simulation theory (Addis et al. 2009) found a functional network, partially overlapped to the Default Mode Network (DMN), that included part of the medial prefrontal cortex (mPFC), inferior frontal gyrus, medial temporal lobes (MTL), polar and posterior temporal cortex, medial parietal cortex and cerebellum, and which was engaged in simulating both past and future events, suggesting that any kind of mental simulation is capable to activate brain regions within the DMN. The Authors also investigated the cerebral networks underlying two different phases of recalling a past event or imagining a future event, i.e., the construction and the elaboration processes. In the construction phase, participants mentally re/constructed the event and, once they had it in mind, they retrieved or imagined further details in the elaboration phase. Results showed that the construction phase for both kinds of events elicited the activation of hippocampus, inferior parietal lobule, middle occipital gyrus and superior occipital gyrus/cuneus. The elaboration phase activated the frontopolar and inferior parts of the mPFC (BA 10 and 11), the temporal pole and the middle temporal gyrus, hippocampus, parahippocampal gyrus, cingulate/retrosplenial regions, precuneus and inferior parietal lobule (Addis et al. 2007). These studies showed that the left hippocampus mediates both past and future events construction, together with posterior visuospatial regions in occipital and parietal lobes, whereas the right hippocampus and right frontopolar and left ventrolateral prefrontal cortices activate specifically for episodic future thinking (Addis et al. 2007). On the other hand, a later study (Addis et al. 2011) identified two circuits within the DMN, suggesting the existence of a "remembering subsystem", which consists of hippocampus, parahippocampal gyrus and widespread regions of posterior visual cortex, and an "imagining subsystem", which comprises the anterior hippocampus and widespread medial prefrontal and parietal regions.

Emphasising the spatial and scene-related processing within MTT, the fMRI studies conceptualised according to the scene construction theory showed a common distributed network of scene construction which involved the hippocampus, parahippocampal gyrus, lateral temporal and inferior posterior parietal cortices, as well as retrosplenial cortex, anterior medial prefrontal cortex, and posterior cingulate cortex (Benoit & Schacter, 2015; Hassabis et al., 2007; Hassabis & Maguire, 2009). An involvement of anterior mPFC, posterior cingulate cortex (PCC), and precuneus was found specifically in episodic memory and future imagination (Hassabis et al. 2007a, 2007b). This commonality of brain activity between remembering the past and imagining the future suggests that these regions are related to the self and the context of the episodic scene, irrespectively of the temporal factor (Hassabis et al. 2007b; Hassabis & Maguire, 2009). In addition, clinical evidence showed that patients with bilateral hippocampal damage were impaired both in remembering the past and in imagining new experiences. The Authors concluded that the hippocampus is the main hub of a network which mediates the scene construction mechanisms, owing to its role in processing spatial information and binding together elements from an imagined complex scene (Hassabis et al., 2007b; Maguire and Mullally, 2013). Furthermore, the role of ventromedial prefrontal cortex (vmPFC) was also investigated in MTT literature. Bertossi and colleagues (2016) showed that patients with a vmPFC lesion were unable to construct both past and future events, highlighting the involvement of this area in constructive processes supporting both past and future MTT. Finally, asking participants to imagine scenes with a different number of elements, three distinct subnetworks for scene construction were identified through fMRI studies. The first one comprises the hippocampus and the retrosplenial cortex, activating similarly irrespective of the number of elements in a scene; the second network includes intra-parietal sulcus and angular gyrus, showing higher activation for the increasing number of elements in the scene; and the third circuit engages the lateral PFC, activated only after imagining a second scene element (Summerfield et al. 2010).

The importance of the autonoetic consciousness in MTT processes has been underlined in one of the last studies by Tulving and colleagues (Nyberg et al. 2010), where participants inside the MRI scanner were trained to picture to have a walk along a familiar path, varying the moments in time in the Present, in the Past or in the Future. The fMRI results showed that "walking" in the Past and in the Future, compared to the Present, activated left frontal and parietal areas. On the contrary, medial temporal regions did not show differences across the temporal moments. Furthermore, analysing the functional connectivity within the DMN revealed two functionally distinct subsystems: the first one was related to affective, self-referential and social processes, and comprised frontal and parietal regions; whereas the second one was related to the mnemonic processes, and encompassed the middle temporal lobes (MTL), including the hippocampus (Andrews-Hanna et al. 2010). Indeed, as compared to past events, future events are expected to engage generative and imaginative processes to support the creation of novel and likely events (Addis et al., 2007b, 2009). Namely, it was proposed that the construction of novel and detailed future events can be dissociated from other forms of simulation and recall (Addis, 2020).

Following the Self-Projection theory, neuroimaging results during the MTT task identified a common neural network engaged in self-projecting to the different moments in subjective time (Past, Present and Future), which included the right anteromedial temporal lobe, bilateral posterior parietal cortex, left inferior frontal cortex, right temporo-parietal junction (TPJ), insular cortices and occipitotemporal cortices bilaterally (Arzy et al. 2008, 2009a; Gauthier and van Wassenhove, 2016b). Notably, the bilateral posterior parietal cortices and right anteromedial temporal lobe activated as a function of the Self-Projection condition, while a Self-Reference effect was found in posterior parietal cortex and insular cortex bilaterally and left inferior frontal cortex (Arzy et al. 2009a). Furthermore, recording intracranial electroencephalogram (iEEG) during MTT, Schurr and colleagues (2018) found a time dissociation in the left hemisphere between lateral temporal electrodes (activated at about 100-300 ms) and hippocampal electrodes (activated at about 400-600 ms). Thus, the lateral temporal cortex was involved in the early MTT, that is, in the Self-Projection phase of the task, then the hippocampus activated later, in the Self-Reference phase, when participants relate the different events to the “projected” self.

Finally, clinical studies on brain damaged patients highlighted different aspects of the ability of Self-Projection in time. A patient with subacute bilateral MTL lesions was able to mentally project in different temporal locations, although she was impaired in memory functions, suggesting that MTL only partially contributes to Self-Projection in time (Arzy et al. 2009c). On the other hand, another patient with bilateral hippocampal damage was unable to imagine herself in the near or far future or remembering experiences from the near past, despite her episodic memory for earlier events being intact. This suggested that hippocampal lesions may equally impair the ability to project to different timepoints (Andelman et al. 2010). Moreover, Ciaramelli and colleagues (2021a, 2021b) showed a more specific role of vmPFC in future oriented MTT. The Authors submitted a group of patients with vmPFC lesions to the MTT task by Arzy et al. (2008) and found out that these patients were selectively impaired in projecting towards the Future and in classifying relative future events.

3. The Spatial representation of Time

Tulving (2005) postulated that Mental Time Travel always takes place not only in subjective time, but also in mental space, referring to the ability to voluntarily disengage from the actual time to recall past events and to picture future scenarios, and suggesting that this ability could rely on the capacity of disengage from the actual spatial location to navigate in different environments. In the same vein, such a capability could be similar to the capacity of disengaging from the personal perspective to adopt those of other people (Buckner and Carroll, 2007), also known as Theory of Mind (Frith and Frith, 2006; Gallagher and Frith, 2003).

A cognitive construct that has been proposed lately and that can combine different metrics is that of Mental Lines (Arzy and Dafni-Merom, 2020).

3.1 Mental Lines

In the last decades, several studies have proposed that space, time, and numbers share cognitive representations, notably on Mental Lines, that is, the way humans represent time and numbers on an horizontal left-to-right oriented spatial axis (Dafni-Merom and Arzy, 2020).

This hypothesis first originated from the spatial representation of numbers on the Mental Number Line (MNL; Banks and Hill, 1974) and has been widely investigated, concluding that the semantic value of numbers is indexed by their spatial position on this line (for reviews Hubbard et al. 2005, de Hevia et al. 2008). Moreover, it has been argued that the spatial orientation of the MNL follows the writing direction; this has been tested by Dehaene and colleagues (1993) with the Spatial-Numerical Association of Response Codes (SNARC) effect, i.e., relatively small numbers lead to faster responses when given with the left hand, while relatively large numbers elicit faster responses when given with the right hand. Furthermore, studies conducted on children and people belonging to archaic cultures engaged in numerical calculations showed that numbers are mapped on a logarithmic scale on the MNL (Dehaene and Cohen, 1995; Dehaene et al., 2008). A similar spatial representation has been proposed for the time on the corresponding Mental Time Line (MTL; Torralbo et al., 2006), where the time flow is oriented left-to-right, thus the past is represented on the left portion of the MTL and the future is associated with the right one, especially in Western cultures (for a review, Bonato et al. 2012). In addition, logarithmic features similar to those present in MNL have been found in the MTL (Arzy et al. 2009b; Gauthier and van Wassenhove, 2016).

In conclusion, these findings lead to the suggestion that humans automatically process magnitudes in different dimensions and map this information in representational space, as proposed in A Theory Of Magnitudes by Walsh and colleagues (2003a).

3.2 A Theory Of Magnitudes

The so-called A Theory Of Magnitudes (ATOM) unifies all the evidence of the interaction between space, time and numbers in the brain, and was first formulated by Walsh (2003a, 2003b) and revised by Bueti and Walsh (2009). The ATOM argues that space, time and numbers, as different kinds of quantities, belong to a generalised magnitude system which allows humans to compute stimuli in an integrated manner for action planning. It has been suggested that this system is located in the parietal cortex, which works as a metrical map when quantities have to be measured, irrespective of the specific domain (space, time or numbers). The overlap between these processes enables us to analyse environmental information to organise a motor output. Moreover, this shared metrical map appears to have a spatial nature, which gives a spatial characterization and a spatial order to the dimension considered, allowing the quantification process.

In particular, Bueti and Walsh (2009) focused on the representations of space and time and their interaction in daily life for action. In fact, space and time must be estimated accurately in order to perform sensory-motor transformations useful to act in the environment (e.g., grasping, reaching, pointing, or throwing an object), hence they have to be “coupled metrics for action”. Accordingly, these representations also must be mediated by close and shared brain regions, the parietal cortex (Bueti and Walsh, 2009).

Within the last two decades, the ATOM gave rise to numerous studies on the coupling between space and time.

3.3 Space and Time interactions

Temporal durations

Several studies reported an association between temporal duration and spatial location. In duration judgement tasks, participants were asked to identify different durations (either 1 or 3 seconds) pressing a key with either their left or right hand. The results showed that short temporal intervals led to fast responses when answering with the left hand, and vice versa, long temporal intervals led to fast responses when answering with the right hand (Conson et al. 2008; Vallesi et al. 2008). This facilitation suggests that the passing of time is cognitively mapped in a spatial representation, coherent with the representation of the motor response. However, these spatial associations appeared to involve a left-right spatial position related to the effectors, rather than an absolute location. Indeed, the same behavioural effect was observed when responses were given with crossed hands or with two fingers of the same hand (Vallesi et al. 2008). These associations can be influenced by repetitive Transcranical Magnetic Stimulation (r-TMS) of the right posterior parietal cortex (PPC). Oliveri and colleagues (2009a), in a duration bisection task, asked participants to set the midpoint of a time interval reproducing half of the duration, while their right PPC could be stimulated either in the encoding or in the retrieval phase of the time interval. These Authors showed that when right PPC was stimulated during the retrieval phase, participants underestimated the reproduced time interval, that is, subjects made the temporal bisection of the interval forward in time. Thus, they concluded that right PPC plays a specific role in temporal bisection, especially during retrieval of the interval to be bisected, representing one of the neural correlates of the spatial-temporal interactions. In addition, Magnani and coworkers (2011) found that following a focal lesion in the right hemisphere, patients were selectively impaired in temporal estimations, presenting the tendency to underestimate real durations. These lesions involved temporo-parietal areas, consistently with findings by Bueti and Walsh (2009). Furthermore, Oliveri et al. (2013) reported that neglect patients tend to underestimate temporal durations during a bisection task. These Authors suggested that the spatial attentional deficit biases the representation of time on the MTL, with a distorted representation of the left space. Accordingly, patients may neglect the left/first part of the MTL as they do with spatial lines (Berti et al. 1995), thus reproducing longer intervals. Finally, Vicario and colleagues (2008) reported that the duration of visual stimuli was underestimated when presented on the left and overestimated when on the right. Therefore, the metrical interaction between space and time is evident also when no action is required, that is, at a purely cognitive level, and the coupled spatial-temporal metric for mere action proposed by Bueti and Walsh with the ATOM (2009) has been overcome.

Past and Future representations on the Mental Time Line

In support of the spatial representation of time, an association between left and right and the temporal concepts "before" and "after", as well as "Past" and "Future", has been proposed. Accordingly, the left and the right portions of MTL are associated with before and Past, and with after and Future, respectively. In this case, the spatial aspects related to time concepts (i.e. left-short and right-long) suggest that time can be represented on a left-to-right temporal mental line, which cannot be considered a mere example of the mental number line (Bonato et al. 2012). Notably, Santiago et al. (2007) asked participants to give a left or right manual response to past or future words or brief sentences (e.g., yesterday vs tomorrow; he said vs she will say) and found that motor responses were facilitated when word position and response effectors were congruent with left-Past and right-Future conceptual analogy. Similarly, Ouellet and colleagues (2010a) showed that activating the Past and Future concepts through visually projected words induce a priming effect in motor responses, to the left and right, respectively. Furthermore, this space-time congruency effect is extended to event sequences, e.g., videos or series of pictures: asking participants to judge the temporal order of an event as respect to another one presented (Santiago et al. 2010), again, responses were faster when participants responded with their left hand for “before”, and with their right hand for “after”, and this suggests that the spatio-temporal association does not arise only for overlearned sequences. Further evidence derives from the Spatial-Temporal Association of Response Codes (STEARC; Ishihara et al. 2008). During the task, participants were instructed to press one of two response keys (either left or right) to distinguish if the onset of a probe stimulus following periodic auditory clicks occurred earlier or later than expected, as compared to the previous clicks intervals. The left-earlier and right-later association was demonstrated again. Recently, Scozia and colleagues (2023) extended the STEARC effect to the semantic classification of words referring to the Past or to the Future, demonstrating faster reaction times for Past/Future words when responding with left/right hand, respectively. The Authors found that when cognitive resources are involved in the semantic judgement of Past and Future concepts, the STEARC varies as a function of the speed of these decision processes. This suggests that the activation of the left-to-right spatial representation of time emerges in the late phase of decision time processing.

The studies on the chronometrical component of the Mental Time Travel ability (MTT), Self-Projection and Self-Reference (Arzy et al. 2008; 2009a; Anelli et al. 2016a; 2016b), contributed to support the spatio-temporal association. Most of these studies adopted the above mentioned MTT task proposed by Arzy and colleagues (2008), where participants are asked to judge if life events took place before or after (Self-Reference component) an imagined self-location in time (Past, Present or Future; Self-Projection component). When projecting to a different temporal moment as respect to the present time, an egocentric remapping of the temporal context is required, and accordingly the mental egocentric perspective on life events changes. Indeed, the same event can be judged differently as past or future relatively to the self-location in time, as an example the 40th birthday can be a future event for a 35 year old person in the Present and in the Past (10 years ago), but it will be classified as past if this person adopts a Future time-locations (10 years from now). The behavioural findings confirmed the further cognitive effort of projecting and remapping the time locations, in fact RTs and error rate increased in the Past and in the Future Self-Projections, as compared to the Present one

(Arzy et al. 2008, 2009a; Gauthier and van Wassenhove, 2016a, 2016b). On the other hand, responding to relative future events led to faster RTs as compared to relative past events. Interestingly, a further effect was consistently found in MTT tasks: the "temporal distance" (TD) effect. Authors observed that the more distant an event to the Self-Projection time point (Present, Past and Future), the faster the RTs (Arzy et al. 2009b) and the more accurate the performance at the task (Gauthier and van Wassenhove, 2016b). Notably, Arzy and colleagues (2009b) found that RTs are logarithmically distributed as a function of event temporal distance from the adopted self-location. Since in the numerical domain evidence of a logarithmic scaling of numbers during calculations suggested a spatial mapping of numbers on the Mental Number Line (Banks and Hill, 1974; Dehaene et al. 1995), in analogy with the representation of physical quantities, Arzy and colleagues (2009b) concluded that the processing of temporal distance relies on similar spatially mapping mechanisms of events on the Mental Time Line. In addition, the fact that the same TD effects were found in the Present time location as well as in the Past and in the Future suggested that humans automatically travel along the MTL, and that Self-Projecting might be perceived as picturing oneself in specific points on this line (Arzy et al. 2009b), strengthening the hypothesis of underlying spatial mechanisms in time processing and MTT. Along with the brain activations related to the Self-Projection and Self-Reference components reported above in paragraph 2, the activation of the right temporo-parietal junction (right TPJ) was found to be a function of the temporal distance between the Present moment and the events considered (Arzy et al. 2009a). This finding suggested a pivotal role of this region in coordinating the relation between imagined and actual temporal location (Arzy et al. 2009a).

Moreover, Gauthier and van Wassenhove (2016a; 2016b) implemented a Mental Space Navigation (MSN) task similar to the MTT task to compare Self-Projection processing in both space and time. In the MSN, participants were requested to self-project to different spatial locations (e.g., Paris as the present location; Cayenne as the west location; Dubai as the east location) and judge whether a series of events occurred at the relative west or east of the adopted location. Similar Self-Projection and Self-Reference behavioural effects (RTs and Error Rate, ER) were found when considering MSN only (Gauthier and van Wassenhove, 2016a), however when alternating blocks of MTT and MSN tasks in the same session, an interaction between time and space was found for Self-Projection but not for Self-Reference (Gauthier and van Wassenhove, 2016b). Thus, these Authors concluded that time and space share similar map transformation processes involved in Self-Projection, but cognitive domain-specific mechanisms compute spatial and temporal mental distances. In the same vein, despite the similar fronto-parietal network activity elicited by MTT and MSN, Gauthier and van Wassenhove (2016b) reported adjacent yet distinct brain regions mediating time and space mental travels, except for a subregion of the right inferior parietal lobule (right IPL) whose activation was found in both tasks.

Nonetheless, subsequent studies kept reporting evidence of the interaction between space and time, specifically in the MTT capacity. As previously mentioned, neuropsychological studies showed that normal ageing and brain lesions can affect the MTT. Anelli and colleagues (2016a) submitted healthy older participants to the MTT task (Arzy et al. 2008) and found that the elderly performed worse in both future Self-Projection and Self-Reference as compared to young adults. The difficulties with relative future events have been related to a loss of the future preference typically observed in MTT, since older adults could be less motivated and oriented to future happenings because of a sense of limitedness of their time (Anelli et al. 2016a). Furthermore, the Authors interpreted the age-related effect on Self-Projection as a consequence of the higher involvement of executive functions and self-related information required for future mental constructions, which are impaired in the elderly because of a decline of functionality in the Default Mode Network. This was confirmed by the neuropsychological findings by Ciaramelli and colleagues (2021a; 2021b), who identified the specific role of the ventromedial prefrontal cortex in future-oriented MTT.

Moreover, impairments in time processing have been observed in brain damaged patients with hemispatial neglect, who show a deficit in orienting visuo-spatial attention towards the contralesional space, which appears to extend to the temporal domain (Basso et al., 1996; Becchio and Bertone, 2006; Danckert et al., 2007; Oliveri et al., 2009a; Magnani et al. 2011; 2013). Specifically regarding the ability to mentally travel in time, Anelli and colleagues (2018a; 2018b) submitted a group of right brain-damaged patients with neglect to the MTT task and found that they were slower and less accurate when responding to relative future, as compared to relative past events. Following the hypothesis of a left-to-right oriented MTL, this finding appears counterintuitive, because a difficulty is expected with relative past events, which should be located on the left portion of the MTL. However, this performance can be explained by the coexistent deficit of spatial working memory, which worsens the rightward attentional bias. Indeed, neglect patients may spend more time exploring the right space, where relative future events are represented, leading to slower responses and more errors due to recursive search and false recognition. Finally, this study raises another important topic supporting the spatial representation of time at a high cognitive level, i.e., the role of spatial attention in mediating the interaction between time and space.

Nature or Nurture

The association between time and space is commonly used in language, for example in sentences such as “They moved a meeting forward two hours” (Casasanto and Boroditsky, 2008), suggesting that time is spatially shaped by culture and in the linguistic domain. Notably, it has been argued that every piece of evidence presented so far demonstrates only that the left-to-right oriented spatial representation of time is shaped by the cultural writing direction. Indeed, the writing direction appears to evoke the representation of sequential events (Fuhrman and Boroditsky, 2010; Ouellet et al., 2010b; Tversky et al., 1991). Ouellet and coworkers (2010b) asked Spanish and Hebrew speakers to discriminate temporally featured words, such as “past” or “future”, presented in auditory modality, and to give lateralized responses by pressing a left or right key. Their results showed for Spanish participants (who write left-to-right) the expected left/past and right/future association, whereas Hebrew participants (who write right-to-left) showed an opposite pattern of space-time association. In addition, the association between time representation and writing direction was found in a group of Mandarin participants, whose representation of time is conceived on a vertical spatial axis

(Boroditsky et al., 2011). On the other hand, Anelli and colleagues (2018b) submitted left-to-right and right-to-left readers and writers to the MTT task associated with a STEARC protocol (i.e., past/left hand response vs future/right hand response and vice versa), but the response facilitation was recorded only for left-to-right participants and not for right-to-left participants. The Authors suggested that the latter participants actually have “hybrid” reading and writing habits, which might have decreased the STEARC effect. Alternatively, this result might reflect the existence of an “innate” left-to-right organisation of the MTL, which is influenced, but not overcome, by cultural aspects.

In addition, the linguistic factors are not the only cultural aspects which can affect the time-space association, and furthermore this association has been described in contexts where culture was not relevant. Indeed, Lourenco and Longo (2010) observed that 9 month old children showed a preference for binding longer temporal durations with stimuli larger or longer in size, or more numerous. Thus, this tendency cannot be mediated by the use of words, and this could represent an evolutionary re-use of the spatial representations for general purposes (Srinivasan and Carey, 2010). Moreover, different animal species appear to prefer left-to-right sequential order of items, suggesting a probable hemispheric asymmetry instead of a representational mental line (Rugani et al. 2010; 2011). This points out the possible role of neurological constraints which might contribute to shaping the association of spatial representations to time and quantities.

Role of Spatial Attention in the space-time interaction

The previously presented studies led to the suggestion that time-space interaction arises when the temporal task shows spatial features, regardless of whether the spatial aspects are related to a lateralized motor response or target. Accordingly, it has been widely demonstrated that spatial attention represents the medium for accessing and manipulating these spatial representations of time. Spatial attention consists of the capacity to identify locations and objects in the space that are relevant for behavioural responses and enables a better processing of the selected spatial information.

In the numerical domain, spatial attention is considered the cognitive mechanism which permits movements along the spatially organised MNL (Zorzi et al. 2012; Umiltà et al. 2009), however, it is still unclear whether shifts in spatial attention precede or follow the processing of numerical magnitudes (Bonato et al. 2012).

In the temporal domain, a series of studies has been conducted on both healthy subjects and brain-damaged patients, to investigate how the modulation of spatial attention affects temporal perception and the ability to mentally travel in time. Prismatic Adaptation is one of the procedures used to manipulate spatial attention in general, and in the temporal domain in particular.

Prismatic Adaptation procedure

The Prismatic Adaptation (PA) procedure is a visuo-motor technique typically used in the rehabilitation of hemispatial neglect (Frassinetti et al. 2002), since it manipulates spatial attention. During PA, participants are asked to perform a reaching task towards a target while wearing deviating prisms, that is, lenses that deviate the visual field in a specific direction. Namely, participants are required to execute a pointing movement as accurately and as fast as possible to reach a target presented by the experimenter in different spatial positions. In the first phase, “Exposition phase”, participants commit several pointing errors, since their field of view is shifted and their movements are shifted in the same direction, therefore the real position of the target is missed. In this phase, visual feedback on the participants’ movement and thus on the errors is necessary. Indeed, after a few trials, adaptation to the lenses occurs, i.e., a shift of visual and proprioceptive spatial coordinates: the pointing displacement decreases (Error Reduction - ER), and finally participants precisely point to the target, despite the use of the lenses. The reduction of the error is due to a fast process activated by the discrepancy between the target position and the position of the pointing movement (Error Feedback). Once the prismatic lenses are removed, subjects show a pointing deviation opposite to the visual shift induced by the lenses (After Effect - AE). Several studies have suggested that the PA affects not only the visuo-motor level, but also the spatial attentional and spatial representational level (Serino et al. 2006; Pisella et al. 2006). Several models have been proposed to describe the sensory-motor mechanisms involved in PA. According to the main interpretative hypothesis by Redding and Wallace (1997a; 1997b; 2000; 2005), two behavioural mechanisms are engaged in PA. The “recalibration process” appears to compensate for the mismatch between visual input and motor command to reach objects. This is an immediate reaction to the prism-induced deviation through a strategic-cognitive modification of the motor plan to quickly reduce errors. That is, subjects encode the information resulting from the feedback of each movement, with the aim to update further movements, taking the visual shift into account (Panico et al. 2020). “Spatial realignment” is the second mechanism required to align visuo-motor proprioceptive-motor reference frames when the spatial relationships between them change. Spatial realignment is a slow and automatic mechanism which realigns the sensory maps during prism shift, allowing the correction of motor plans (Panico et al. 2020). Therefore, the sensorimotor technique of PA is usually adopted both to investigate neural plasticity in healthy subjects, and to affect visuo-spatial attention deficits at the visuo-motor as well as at the cognitive level in neglect patients (Colent et al. 2000; Jacquin-Courtois et al. 2013; for a review, Panico et al. 2020).

A wealth of studies was conducted to investigate the neural mechanisms underlying the effects of PA. The functional neuro-imaging works focused on changes in brain activity during and after exposure to the prismatic lenses. Notably, they mostly investigated which brain regions participate in the sensory-motor mechanisms of error detection, error compensation (i.e., recalibration), adaptation (realignment) and after-effect (Clower et al. 1996; Danckert et al. 2008; Luauté et al. 2009; Chapman et al. 2010; Pisella et al. 2004; 2006), as well as in the expansion of PA effects to the cognitive level (Luauté et al. 2006; Saj et al. 2013; Crottaz-Herbette et al. 2014; 2019; Clarke and Crottaz-Herbette, 2016; Tsujimoto et al. 2018; 2019). On the other hand, the neuro-stimulation studies provided insights about the mechanisms which facilitate or inhibit the PA procedure and effects (Ferrucci et al. 2015; Van Dun et al. 2017; Panico et al. 2016; 2018a; 2018b; 2019).

In the light of all these pieces of evidence, Panico and colleagues (2020) proposed a model of the neural substrates mediating PA. Firstly, the cerebellum is involved in processing the movement errors, compensating for the optical shift in the early phase of the exposure to prismatic lenses, thus providing an online control. Simultaneously, parietal regions participate in adjusting the movement direction based on previous errors. Both in cerebellum and in parietal areas, separate regions cooperate for the recalibration and realignment processes. The realignment could also be mediated by the superior temporal gyrus and superior temporal sulcus. Once the realignment is completed, the cognitive effects of PA emerge by means of bottom-up activation of middle temporal gyrus, temporo-occipital region, and prefrontal areas.

Effects of the modulation of Spatial Attention on Time representation

The first study demonstrating that the shift of spatial attention induced by PA affects the spatial representation of time has been conducted by Frassinetti and coworkers (2009) through a time reproduction task, where a visual stimulus was presented for a variable interval, comprised between 1600 and 2400 msec, and participants were required to encode this duration and then to reproduce either the entire or a half the duration (time bisection task) by pressing a key. These tasks were conducted before and after a PA procedure inducing either a leftward or a rightward shift of spatial attention. When PA induced a leftward shift, an underestimation of time intervals (longer reproduced time) was recorded as compared to the pre-PA performance, whereas following a rightward shift, a temporal overestimation was recorded (shorter reproduced intervals). According to the spatial representation of time, shifting attention along the MTL modulates time processing as a function of the deviation of prismatic lenses. The same effects were also found in sensory modalities not involving visuo-motor coordination, such as auditory time. Magnani et al. (2012) asked subjects to judge durations as short or long, in a spatial experiment when the stimulus occupied a specific location in space (left or right) and in a tonal experiment when the stimulus was of a specific pitch (high or low frequency). The effects of PA were recorded on the performance: attentional shifting deviations induced underestimation (left) and overestimation (right) in both experiments, suggesting that PA influences the sensory representation of auditory durations and transfers them at a cognitive level. Concerning neuropsychological evidence, the tendency to underestimate durations as a consequence of hemispatial neglect was highlighted by the previously mentioned work by Oliveri and colleagues (2013). In this study, the Authors also submitted right brain-damaged patients with and without neglect to PA and found that a leftward shift of spatial attention augmented temporal underestimation in patients without neglect but decreased time underestimation in patients with neglect. Therefore, these Authors proposed a model to explain dysfunctional time processing in right brain-damaged patients. According to this model, in healthy subjects real and perceived initial point of time are aligned, and time flow proceeds with the same speed throughout the time interval. In right brain-damaged patients, too, real and perceived initial point of time are aligned, but the passage of time of the perceived interval beats more slowly than the real one, and this leads to underestimation. Finally, in right brain-damaged patients with neglect, a misalignment between real and perceived initial point of time occurs, since the first portion of the time flow of the perceived interval is neglected and missed. In addition, the same slower perception of time flow occurs, as in the other right hemisphere lesions. Thanks to the PA procedure, which induces a leftward shift of spatial attention, patients with neglect can rebalance their spatial attention bias and reduce the neglected portion of the time interval.

Regarding the MTT ability, the above-mentioned studies by Anelli and colleagues (2018a; 2018b) showed that neglect patients were significantly impaired in responding to relative future events, due to the coexistence of a spatial attentional bias and of a spatial working memory deficit, leading to recursive search and false recognition in the right portion of the MTL. However, the Authors also demonstrated that PA reduced the impairment in the MTT ability, by facilitating the exploration of the left portion of MTL and improving the correct location of relative past and relative future events in time. In addition, long-term therapeutic effects were demonstrated through a PA treatment comprising ten sessions, one each day, over a period of two weeks (Anelli et al. 2018b). The effects of PA on the MTT ability were also demonstrated on healthy young adults (Anelli et al. 2016a). Two groups of university students were submitted to the MTT task before and after a rightward or leftward shift of spatial attention, induced by a single session of PA per group. The results showed that also in healthy participants the PA procedure can affect the cognitive representational level, modulating the ability to mentally travel in time. In fact, the group of participants submitted to a leftward shift of spatial attention showed an improved performance in responding to relative past events, whereas those undergoing a rightward shift of spatial attention were facilitated when responding to relative future events.

However, the neural mechanisms mediating the effects of PA in MTT in healthy as well as in brain damaged subjects have not been investigated yet.

Objectives of the thesis

In the previous chapters, the state of the art about the ability to mentally travel in time has been presented. This overview went through the theoretical frameworks which explain how humans perceive and represent time and mentally travel in time, then illustrated the experimental and clinical evidence of the effects of the modulation of spatial attention in the temporal domain. A special focus was dedicated to the representation of the temporal concepts of Past, Present and Future, and to the cognitive abilities of Self-Projection and Self-Reference in MTT. Relevance was given to the neuroimaging studies identifying the neural substrates of time perception, of MTT and of the effects of the prismatic adaptation technique on the perception of temporal duration.

Despite this amount of evidence, several questions are still open. The aim of the present thesis is to deepen the exploration of the neural bases of MTT and to evaluate the different factors which can modulate this capacity.

In the first experiment, we investigated which neural structures mediate the effects of the PA-induced shift of spatial attention in MTT in healthy individuals. Namely, we designed a fMRI protocol with a revised version of the MTT task by Arzy et al. (2008), and we investigated brain activity before and after a single session of prismatic adaptation inducing a leftward shift of the spatial attention. We finally proposed an anatomo-functional model of the modulation of the neural substrates involved.

In the second experiment, we focused on the behavioural effect of the individual perception of the temporal distance; our aim was to understand how subjects respond to events on the MTL as a function of how they perceive them near or far in time. We also investigate how this personal perception of distances modulates the brain network involved in MTT.

Experiment 1

Spatial Attention Modulation of the Brain Network Involved in Mental Time Travel

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Introduction

We constantly re-evoke previous experiences and anticipate future possibilities to appropriately respond to stimuli in our environment. This ability is defined as Mental Time Travel (MTT), i.e., the human capacity to relocate themselves into another temporally specified location, both to the past and to the future (Dafni-Merom and Arzy, 2020; see also Addis et al., 2007; Schacter and Addis, 2007; D'Argembeau, 2020; Garcia-Pelegrin et al., 2021). It is widely accepted that moving to the past during MTT requires episodic autobiographical memory, that is, the ability to re-experience personal past events, whereas moving to the future requires "episodic future thinking", that is, the ability to project oneself forward to a potential future (Fellows and Farah, 2005; Buckner and Carroll, 2007; Gilbert and Wilson, 2007). The resulting capacity of reconstructing past events and anticipating possible scenarios also depends on semantic memory, as the envisioned events need to be consistent with the general knowledge of oneself and of the world (Suddendorf and Corballis, 2007).

In addition to these cognitive functions, it has been suggested that spatial representations shape time processing. According to this hypothesis, we represent temporal events on a spatially oriented line. Indeed, both temporal duration (short/long) and temporal concepts (before/after, past/future) can be represented along the Mental Time Line (MTL), a spatial continuum with a left-to-right spatial order, especially in western culture (Lakoff and Johnson, 1999; Oliveri et al., 2009; Bonato et al., 2012, 2016). Coherently with this hypothesis, MTT would consist in travelling along such a mental line, where past events are located on the left of future ones (Torralbo et al., 2006; Santiago et al., 2007; Arzy et al., 2008, 2009a, 2009b; Ouellet et al., 2010).

To better understand the mechanisms underlying MTT, Arzy and colleagues (2009b) implemented a functional Magnetic Resonance Imaging (fMRI) paradigm in which participants were asked to “project” themselves to past, present, or future moments in time (Self-Projection). Then, they were required to determine whether a given event had already happened (relative past) or had yet to happen (relative future) with respect to the assumed specific Self-Projection in time (Self-Reference). Assuming a different time perspective, that is, projecting ourselves into the future or into the past, requires a cognitive effort that we pay in terms of accuracy and speed (“switching cost”): participants’ performances get worse in Past and Future than in present Self Projection (Arzy et al., 2008; Anelli et al., 2016a, 2016b; Gauthier et al., 2019; Ciaramelli et al., 2021a). When projecting oneself in time, humans not only recall and predict events, but also change their mental perspective on life events. Thus, the same events can be located differently in the past or in the future: for example, the last five years events are future if we project ourselves back to ten years ago, or they are past events if seen from the present time.

Moreover, it has been proposed that the spatial time representation is accessed through spatial attention mechanisms (Bonato et al., 2012). In support of this hypothesis, the shift of visuo-spatial attention induced by the prismatic adaptation (PA) technique (Rossetti et al., 1998; Rode et al., 2001; Frassinetti et al., 2002; Pisella et al., 2006; Serino et al., 2007; Patané et al., 2016; Schintu et al., 2017) has been demonstrated to affect MTT (Anelli et al., 2016b). During the PA procedure, participants are asked to perform repetitive pointing movements toward a visual target while wearing a pair of goggles with prismatic lenses, which laterally deviate the visual field. Once the prismatic lenses are removed, a contralateral shift of the spatial attention is induced. Notably, Anelli and colleagues (2016b) revealed that after PA inducing a leftward (rightward) shift of spatial attention, participants’ performance in the MTT task improved for past (future) events as compared to before PA.

From a neuropsychological perspective, the effects of PA on MTT were further confirmed in a recent study with neglect patients, who after right brain damage are unable to orient attention toward stimuli presented or represented on the left side (Anelli et al., 2018a; for reviews about the effects of PA on neglect see also Redding and Wallace, 2006; Newport and Schenk, 2012; Rode et al., 2017; Anelli and Frassinetti, 2019; Panico et al., 2020). After a single session of PA inducing a leftward shift of spatial attention, neglect patients improved in correctly locating events on the mental line (Anelli et al., 2018a), suggesting that temporo-parietal areas mediate not only visuospatial but also MTT-related processes. Previous neuroimaging findings on healthy participants showed that a network involving similar areas is active during MTT: the Self-Projection conditions activate the right anteromedial temporal lobe and bilateral posterior parietal cortex, whereas the Self-Reference conditions activate the left inferior frontal cortex, and insular and occipito-temporal cortices bilaterally (Arzy et al., 2009b, see also Gauthier and van Wasshenove, 2016; Gauthier et al., 2019). Furthermore, the prefrontal cortex plays a special role in MTT, as it is specifically involved in processing both future Self-Projection and future Self-Reference, as suggested by neuropsychological studies (Ciaramelli et al., 2021a; Stendardi et al., 2021).

Since there is only behavioral evidence for the effect of spatial attention on MTT, a crucial point needs to be addressed: which functional network mediates the effects of spatial attention on our ability to mentally travel in time. To this aim, we presented healthy participants with a MTT task in a single event fMRI protocol, before and after a session of PA. We hypothesized that PA shifting attention toward the left would induce an advantage in accessing information regarding the past (Anelli et al., 2016b).

At the neural level, we expected a fronto-tempo-parietal network to be involved in MTT. As far as the effect of PA, we predicted a modulation of posterior parietal cortex and superior temporal lobe activity, as suggested by literature on the visuospatial effects of PA (Koch et al., 2008; Luauté et al., 2009; Magnani et al., 2014). Finally, since the frontal areas are involved in future processing, as suggested by studies on MTT in brain damaged patients (Ciaramelli et al., 2021a), a decrease of prefrontal activity is expected as a consequence of PA shifting attention toward the left.

Materials and Method

Participants

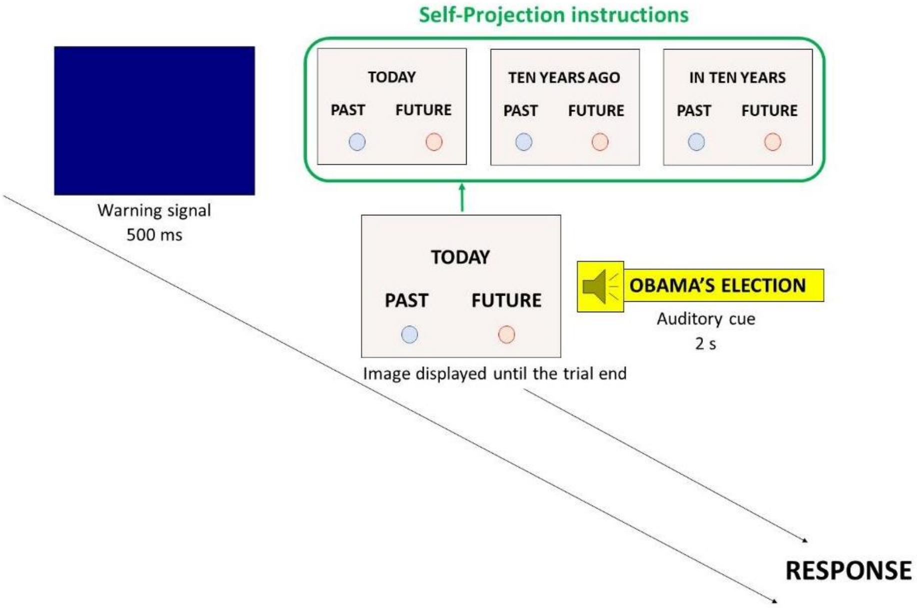
Thirty-eight right-handed (Oldfield, 1971) healthy volunteers, recruited among university students (mean age 24.8, age 19-29; 23 females), took part in the fMRI study. To verify their eligibility to Magnetic Resonance Imaging (MRI) examination, participants were submitted to a clinical history questionnaire, according to the University Hospital of Modena guidelines, in order to exclude the presence of ferro-magnetic clips, implants, electrodes or devices on the body, and claustrophobia. Other exclusion criteria were: history of neurologic or psychiatric disorders or brain trauma, alcohol or drugs abuse. The sample size was set by means of a priori power analysis on G*Power 3 with a repeated measure ANOVA model, (effect size $f=0.25$, $\alpha= 0.05$, and power= 0.85). The sample size is also adequate for fMRI analysis according to Friston's study (2012). One participant was excluded from the analysis because of large head movements during the scanning sessions. All participants gave their written informed consent to their participation. The study was approved by the local ethics committee (Comitato Etico dell'Area Vasta Emilia Nord – Authorization code number: CE 134/2014/SPER/AOUMO) and was conducted in accordance with the ethical standards of the Declaration of Helsinki (World Medical Association Declaration of Helsinki, 2013).

Procedure

Participants underwent an adapted version of the MTT task (Casadio et al. in press; Anelli et al., 2016b), before and after a prismatic adaptation session (Session condition – Pre-PA vs Post-PA). The MTT task was arranged in a jittered single event fMRI protocol. The entire set of stimuli was presented before the experimental session, in order to avoid novelty effects and to let participants familiarize with the stimuli.

Two sessions of 72 trials each were presented. Each session was comprised of two MRI runs of 8 minutes each, thus a single session lasted 16 minutes. Taking into account the MRI preparation, the average length of the post PA session, from the last trial of PA to the end of the MTT task, was 27 ± 0.5 min (mean ± SEM). This ensured that the entire post PA session was performed within the duration of the PA aftereffects (30 minutes, as assessed by previous studies; Magnani, et al. 2014; see also Terruzzi, et al. 2021). Each trial started with a warning cue, a blue screen lasting 500 ms, then participants were asked to imagine themselves either in the Present or in the Past or in the Future - Self-Projection condition – according to the instructions (either "today" or "ten years ago" or "in ten years"), shown on the screen for the entire duration of the trial and pseudo-randomly alternated at each trial (Fig. 1). Then, participants listened to a brief auditory cue (2000 ms), recorded with the same female voice and presented through MRI compatible headphones, describing either a personal (e.g., thirtieth birthday) or a non-personal event (e.g., Milan Expo). Events were chosen and adapted, because of the passing of time, from a validated list used in previous works (Anelli et al., 2016a, 2016b; Supplemental Table S1 in the Supplemental Materials). Finally, the participants had to classify the event as past or future - Self-Reference condition - relatively to the adopted temporal self-location, responding as quickly and precisely as possible at the end of each auditory cue, using their index or middle fingers on a two-buttons keypad.

Figure 1 Example of a Single Trial



Note: The temporal of a single trial in the MTT task with an example of the three possible Self-Projections (Past, Present, Future). MTT = mental time travel.

To prevent the confounding effects of a possible motor facilitation due to the spatial representation of time, half of the participants used the index finger to respond “past” and the middle for “future”, the other half used the opposite association. Before the experimental task, participants performed a brief practice session of six trials. The inter-stimulus intervals were pseudo-randomised (range 0.5–19.7s) using the make_random_timing.py script from the AFNI (Analysis of Functional NeuroImages) package (https://afni.nimh.nih.gov/). Immediately after the PA procedure outside the scanner, participants performed the same fMRI MTT protocol. At the beginning and at the end of each run, a fixation condition (20s) was introduced, to record a baseline for the fMRI signal. Custom-made software developed in our laboratory (http://digilander.libero.it/marco_serafini/stimoli_video/) was used for stimuli presentation and behavioral data collection. The same software was used to present the visual warning cue and the instructions via the ESys System remote display.

At the end of the experiment, participants completed a questionnaire evaluating their knowledge of the events by asking them to recollect when a given event had happened in the past, or to estimate when a given event is likely to happen in the future. We used this questionnaire to categorize the trial responses of the MTT task for each participant as a function of his/her experience (e.g., in the Present Self-Projection, the “graduation” event stimulus was past for some of the participants, but future for others).

Prismatic adaptation procedure inducing leftward shift of spatial attention

Prismatic adaptation was performed outside the MRI scanner in an adjacent, quiet, and separate room, following the same procedure of previous studies investigating the effects of PA on time perception (Magnani et al., 2013, 2014; Anelli et al., 2016b). It consisted in a pointing task towards a visual stimulus (a pen) in three experimental conditions: pre-exposure to prismatic lenses, exposure and post-exposure. The prismatic goggles induced a 10° rightward deviation of the visual field, and the visual stimuli were presented either straight in front of the participants (0°, center), or 21° to the left or to the right of the center. Participants had to point at the target with their right index finger, from a starting point on their chest, as fast and precisely as possible. The pre-exposure condition was comprised of 60 trials, half of them were in a closed loop (visible pointing, 30 trials) pointing condition, as the participants could see the trajectory of their movement, and half were in open loop (invisible pointing, 30 trials). In the exposure condition, participants had to point at the target while wearing the prismatic lenses in closed loop condition (90 trials). Finally, in the post-exposure condition participants removed the goggles and performed the task again in an open loop condition (30 trials). The experimenter recorded the end position of the subject’s pointing direction.

Control Experiment

Since participants underwent the MTT task twice in the fMRI Experiment, the behavioral improvement found after PA could be due to spurious effects, such as familiarization or task repetition. To rule out this possibility, we conducted a behavioural control experiment on a novel group of participants performing the MTT task, before and after a sham condition.

Thirty-seven right-handed (Oldfield, 1971) healthy volunteers, comparable with our previous sample for age, gender and educational level (mean age 22.9, range 19-27, 22 females), took part in the Control Experiment, after giving their written informed consent. The procedure was identical to the one adopted in the fMRI Experiment, except for the PA exposure, where a pair of goggles with neutral lenses was used. Since these lenses do not induce any deviation of the visual field, they do not affect spatial attention. Furthermore, the Control Experiment was conducted exclusively at the behavioral level as participants did not undergo MRI scanning during the MTT task.

MRI data collection

MRI data were collected on a 3T GE Signa Architect system over two experimental sessions (Pre-PA; Post-PA). Each session was comprised of two runs of 320 volumes and each run lasted 8 minutes, for a total of 16 minutes per session; each functional volume had 46 3mm-thick slices (TR= 1500ms, TE=30ms, voxel size 3x3x3mm). A high-resolution T1-weighted 3D anatomical image (TR= 2184.9ms, TE= 3ms, 46 slices, 1x1x1mm) was recorded for each participant to allow anatomical localization.

Data analysis

Since behavioral and beta values obtained from selected regions of interest (ROIs) of functional data were normally distributed in all conditions (all $p>0.05$ at Shapiro-Wilk test), ANOVAs were run and effect size was indicated as partial η squared (η2p). When the interactions were significant, Duncan post-hoc tests were conducted. Mean values and standard error means (SEM) were reported for each condition.

Behavioral data

In order to obtain a combined, synthetic, and synoptic index, which provides precise information about the performance, the inverse efficiency score (IES) was calculated as the ratio between mean reaction time (RT) and proportion of correct answers: the higher the IES, the worse the performance.

To assess the participants' MTT ability, a repeated measures ANOVA, with Self-Projection (Past, Present, Future) and Self-Reference (past, future) as within-subject factors, was conducted on the IES obtained in the Pre-PA session. To evaluate the effect of PA, we conducted a similar ANOVA on Δ IES, the difference between the Pre-PA and Post-PA session: the higher Δ IES, the better the performance in the Post-PA as compared to the Pre-PA session.

Functional data

Functional data were pre-processed and analyzed using MatLab (Mathworks, 2020) and SPM12 (Wellcome Department of Imaging Neuroscience). The following pre-processing steps were used: slice-time, spatial realignment, normalization to Montreal Neurologic Institute (MNI) template and smoothing with 6mm full width Gaussian filter. Single-subject statistical analysis was performed applying the General Linear Model (GLM), where the time-series data were modeled as a series of events convolved with a canonical hemodynamic response function. Regressors of interest were as many as the combinations of factors, i.e., the experimental conditions. Motor response, errors and head-motion parameters (translations and rotations) were entered as nuisance variables.

Each experimental condition was compared to the baseline and to the other conditions and individual contrast images were used for the whole brain random effect analysis.

Whole brain analysis. A full-factorial ANOVA with Session (Pre-PA, Post-PA), Self-Projection (Past, Present, Future) and Self-Reference (past, future) as factors was conducted on single-subject contrast images. In order to investigate the effects of PA on MTT ability, the following contrasts were considered: Pre-PA>Post-PA; Post- PA>Pre-PA (Magnani et al. 2014).

A double statistical threshold (voxel-wise $p<0.001$ and spatial extent) was applied to obtain a combined significance, corrected for multiple comparisons, of $\alpha>0.05$, as computed by 3dClustSim AFNI routine, using the "-acf" option. A family-wise error (FWE) correction was applied to the contrast Pre-PA>Post-PA.

Regions of interest (ROI) analysis. We evaluated cortical activations in both the Pre-PA and Post-PA sessions in several regions of interest (ROIs, each as an 8 mm radius sphere), extracting betas values with Marsbar (Brett et al., 2002). According to the literature, we selected:

- bilateral inferior parietal lobule (IPL, right x= 36, y= -52, z= 59; left x= -42, y= -70, z= 41; extracted from the Pre-PA vs Post-PA contrast); involved in mediating PA effects, spatial attention and spatial representation of time (Pisella et al., 2006; Arzy et al., 2009b; Crottaz-Herbette et al., 2014; Gauthier and van Wassenhove, 2016; Wilf et al., 2019; Panico et al., 2020);
- left superior frontal gyrus (SFG; x= -3, y= 56, z= 20; extracted from the Pre-PA vs Post-PA contrast), involved in time modulation mechanisms as a consequence of PA (Magnani et al., 2014);
- bilateral superior temporal gyrus (STG; right x= 45, y= -22, z= 5; left x= -45, y= -19, z= 2; extracted from the Post-PA vs Pre-PA contrast), involved in prismatic adaptation mechanisms and spatial attention (Karnath et al., 2001; Luauté et al., 2009; Panico et al., 2020).

Repeated measures ANOVAs were conducted on the beta values of the ROIs with Self-Projection (Past, Present, Future) and Self-Reference (past, future) as within-subjects factors, separately for Pre-PA session and Post-PA session. The same ANOVA was performed including factor Session to compare the Pre-PA and Post-PA. All the coordinates are in the MNI space atlas.

Pearson’s correlation analyses were conducted between behavioral data (IES) and beta values.

Psycho-physiological interactions (PPI) analysis. The PPI analysis identifies brain regions whose activity depends on an interaction between psychological context (the experimental conditions) and physiological state (the time course of brain activity) of the seed region. Since recent findings suggest an involvement of IPL in PA, spatial attention and spatial representation of time (Pisella et al., 2006; Arzy et al., 2009b; Crottaz-Herbette et al., 2014; Gauthier and van Wassenhove, 2016; Wilf et al., 2019; Panico et al., 2020) we used right and left IPL as seeds. For each participant, the signal from the peak voxel in IPLs was extracted from the contrast past-events Past-projection>baseline. A 6-mm radius sphere was built around the activity peak to define a volume of interest (VOI; MNI average coordinates: right IPL: x=36.5, y= -52.1, z=51.4; left IPL: x= -36.9, y=-61.3, z=44.3). Each participant's data were re-modelled with regressors for: the time-course in the seed region (physiological regressor); the experimental condition (past-events Past-Projection>baseline; psychological regressor); the interaction between the experimental condition and the region of interest activation signal (psychophysiological interaction). The latter was chosen as the regressor of interest and the corresponding contrast images of the single-subject PPI analyses were used for the random-effect analysis (one-sample t-test).

Results

We checked for possible differences between females and males both in the behavioural and in the functional data: since we found no significant difference, we analyzed the data from all the participants together.

Behavioral results

Pre-PA session

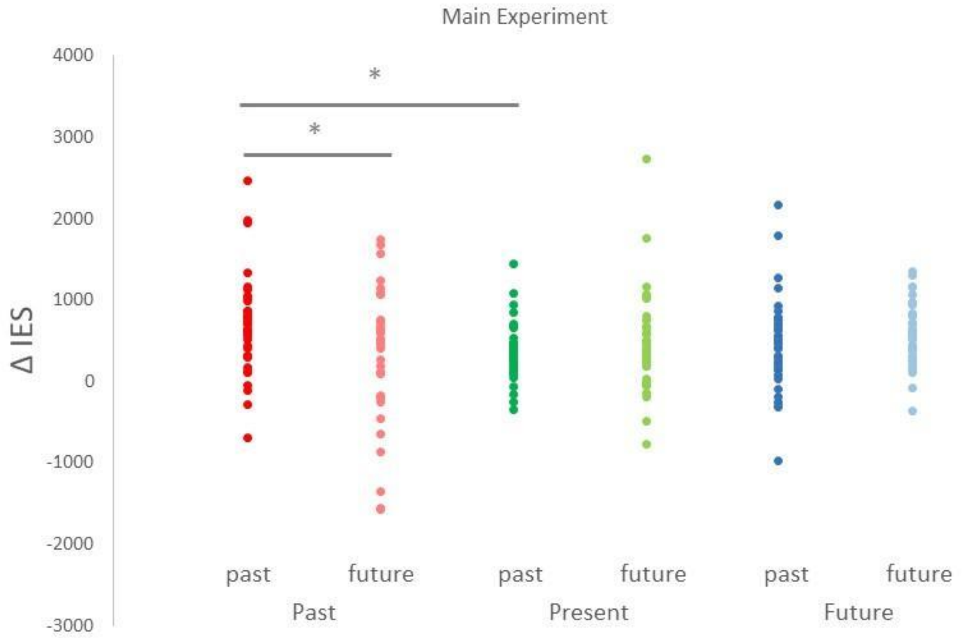
Analysis on IES revealed a significant main effect of Self-Projection ($F_{2,72}$= 72.72, $p < .001$, η^2_p= .67), with all the conditions significantly different from each other (mean value Past = 4491 ± 109, Present = 3684 ± 71, Future = 3907 ± 73). The interaction Self-Projection X Self-Reference was significant ($F_{2,72}$= 8.51, $p < .001$, η^2_p= .19; Supplemental Fig. S1). Post-hoc tests showed that performances for past events were significantly better as compared to future events when participants were projected to the Past (mean 4294 ± 137 vs 4688 ± 122, $p < .001$). Furthermore, when participants were projected to the Future, a significantly better performance was found for future as compared to past events (mean 3784 ± 76 vs 4031 ± 107, p= .04). In the Present projection, performance was comparable for past and future events (mean 3562 ± 82 vs 3806 ± 101, p= .05).

Pre-PA minus Post-PA sessions: effect of prismatic adaptation on the MTT task

Analysis on Δ IES revealed a significant interaction of Self-Projection X Self-Reference ($F_{2,72}$= 4.06, p= .02, η^2_p= .10). Post-hoc tests showed that performance for past events was significantly better than those for future events when participants were projected to the Past (mean 700 ± 99 vs 355 ± 134, p= .02), and for past events when participants were in the Present projection (375 ± 58, p= .03) (Fig. 2). Thus, the interaction revealed an improvement in performance in the Post-PA session for past as compared to future events when projected in the Past.

The main effects of Self-Projection (p= .2) and Self-Reference (p= .7) were not significant.

Figure 2 Behavioural Results of the Main Experiment



*Note. The Self-Projection × Self-Reference interaction on Δ Inverse Efficiency Score (Δ IES). Δ IES values were calculated subtracting IES for post-PA from IES for pre-PA. The higher the Δ IES values, the better the performance after PA. Dark and light colours indicate past and future Self-Reference, respectively; PA = prismatic adaptation. * p < .05.*

Prismatic Adaptation (PA) effect

To verify the effect of PA (the error reduction of the initial pointing deviation in the exposure phase), a series of linear mixed effects models were conducted using the software Jasp (version 0.17.1, 2023) on the mean pointing deviation from the target, expressed in angle degrees, and the participants' random intercept; the trial number (1-30) was added in the model as fixed ordinal variable. To test whether the inclusion of the fixed independent variable trial number increased the model's goodness of fit, likelihood ratio tests (LRT) were conducted. A by-subject random intercept was also added to account for inter-subject variability in the adaptation procedure (Albini, et al., 2022). In the final model on the PA procedure, taking the trial number as fixed effect, we found a significant effect of the trial number ($\chi^2(29) = 1300.87$, $p < .001$), with decreasing deviations from the target, along the PA (see Supplemental Fig. S2).

In order to verify the after-effect of PA, we compared the participants' displacement in the open loop (invisible) pointing in the Post-PA (last 30 trials) and Pre-PA conditions (half of the 60 trials in pre-exposure condition). A paired-samples t-test (two tailed) was conducted to compare the two conditions. A significant ($t(36)= 24.22$; $p < .001$) leftward deviation in the post-exposure was found as compared to the pre-exposure condition (-6.1° ± 0.2 vs -0.5° ± 0.1; Supplemental Fig. S3), as evidence of the PA procedure efficacy.

Control Experiment

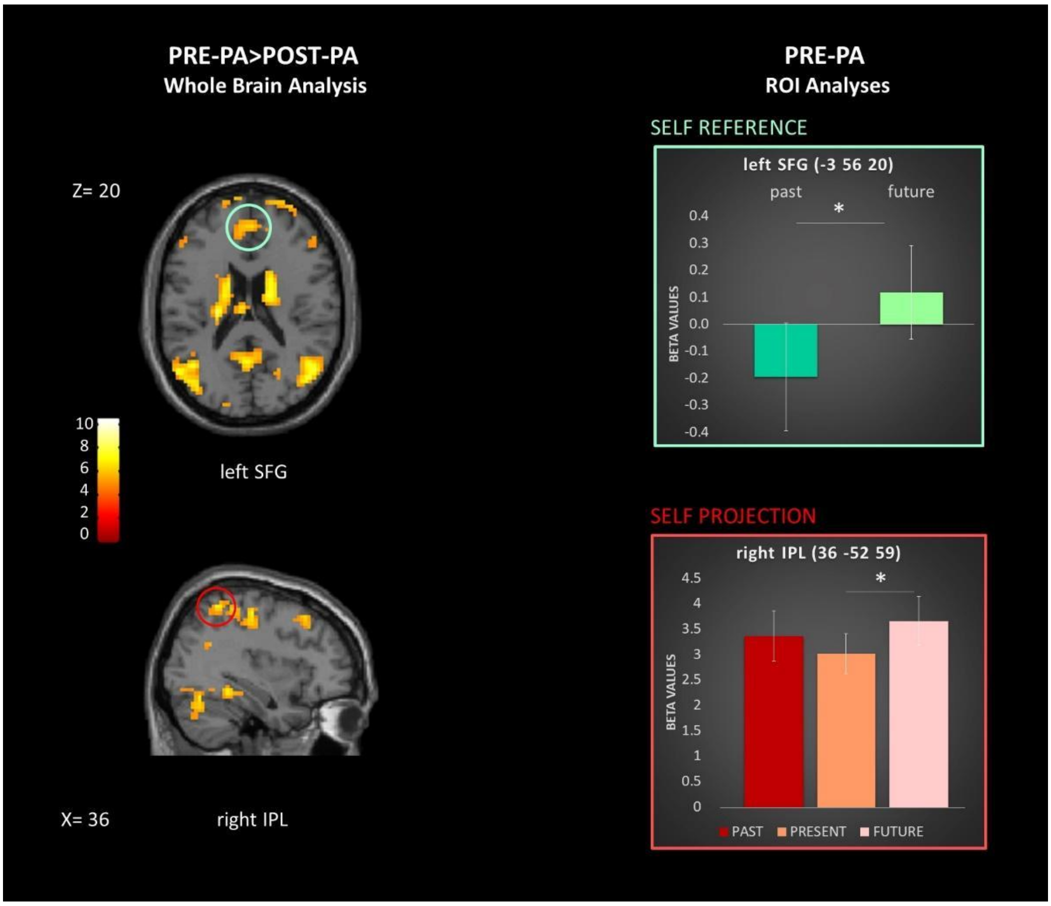
The ANOVA on Δ IES (pre-PA minus post-PA sessions) did not reveal any significant main effect of factors (Self-Projection $p = .2$; Self-Reference $p = .4$) nor interaction ($p = .7$). These results suggested that a repetition or familiarization with the task per se could not explain the effects found in the fMRI experiment.

Functional results

Whole brain analysis: Pre-PA>Post-PA

In the Pre-PA as compared to Post-PA session, a widespread network was activated involving, among others, right parahippocampal gyrus and postcentral gyrus, and bilateral posterior parietal Cortex (the IPLs, angular and supramarginal gyri), precuneus, occipital cortex, cerebellum, basal ganglia, inferior, middle and superior frontal gyri (Fig. 3 left; Supplemental Table S2).

Figure 3 Pre-PA Session Functional Results



*Note. Left: Activations in pre-PA > post-PA contrast p < .05 FWE corrected k > 0, displaying only clusters >10. Right: Bar plots represent ROI analyses results as a function of MTT conditions (Self-Reference in green and Self-Projection in red). Error bars depict standard errors of the mean (SEM). ROI = regions of interest; FWE = family-wise error; MTT = mental time travel; IPL = inferior parietal lobule; SFG = superior frontal gyrus; PA = prismatic adaptation. * p < .05*

ROI Analyses in Pre-PA Session

Right IPL showed a significant main effect of Self-Projection, $F_{2,72} = 4.09$; $p = .02$, $\eta^2_p = .11$, with a higher activation for the Future as compared to the Present projection (Figure 3, Right). Interestingly, the beta values negatively correlated with IES in the Future projection ($r = -0.3$, $p = .03$), indicating that the higher the right IPL activation, the lower the IES, that is the better the performance.

Left STG showed a significant main effect of Self-Reference, $F_{1,\,36} = 7.45$, $p < .01$, $\eta^2_p = .17$, with a higher activation for past as compared to future events.

Finally, analysis on left SFG revealed a significant main effect of Self-Reference, $F_{1,\,36} = 7.59$, $p < .01$, $\eta^2_p = .17$) with a positive activation for future events and a signal decrease for past ones

(Figure 3 right). Right STG and left IPL did not show any significant main effect ($p > .1$ and $p > .2$, respectively).

These results on the MTT task related activity (before PA) indicate that right IPL is more activated when participants were imagining themselves in the Future, whereas left STG and left SFG are involved in the Self-Reference component of MTT when participants responded to past and to future events, respectively.

Whole Brain Analysis: Post-PA>Pre-PA Contrast

The analysis showed bilateral activation in STG underlies the PA effect (Figure 4, left; Table 1).

Table 1 Activations in Post-PA > Pre-PA Contrast

Anatomical region	**BA**	**side**	**K**	Z_E	**Spatial coordinates (MNI)**		
					x	***y***	***z***
Superior Temporal Gyri	41, 22	*r*	125	5.50	45	-22	5
				3.61	51	-31	11
		l	111	4.47	-45	-19	2
				4.26	-42	-25	11
				4.06	-39	-34	8

Note. Areas of increased signal for the post-PA > pre-PA contrast (cluster size k > 109, corrected at α < .05). BA = Broadman area, r= right, l= left.

ROI Analyses in Post-PA Session

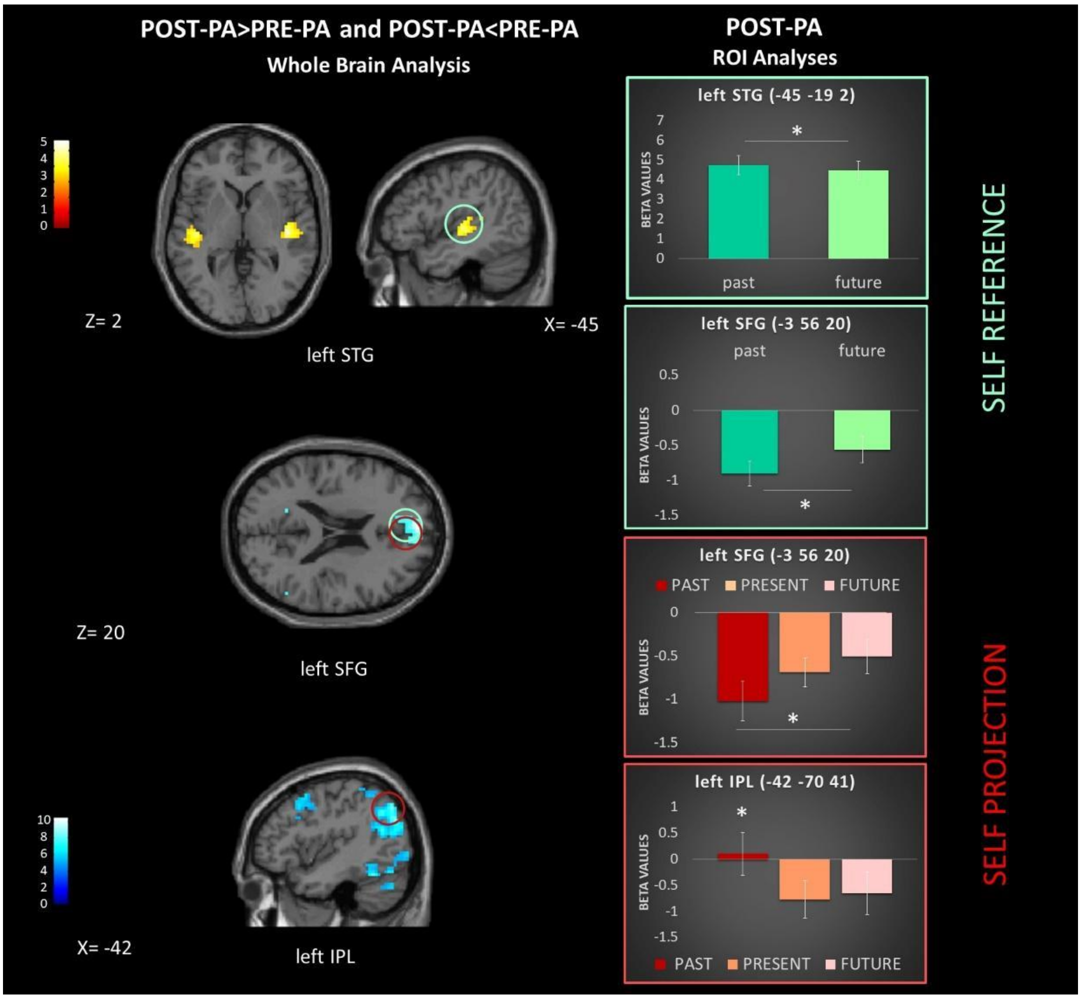
Right IPL did not show any significant main effect (all $p > .07$), indicating that this area was engaged during the MTT task, regardless of any experimental condition. However, beta values of right IPL negatively correlated with the participants' performance (IES) for future events when they were projected to the Past ($r = -0.3$, $p = .05$): the lower the right IPL activation, the worse the performance. In the left hemisphere, IPL showed a significant main effect of Self-Projection, $F_{2, 72} = 5.39$; $p < .01$, $\eta^2_p = .13$) with a positive and higher activation in Past projection as compared to Present and Future projections (Figure 4, Right).

Moreover, analysis on left SFG showed significant main effects of Self-Projection, $F_{2,72} = 4.93$, $p < .01$, $\eta^2_p = .12$, with a greater reduction of activation for Past as compared to Future projection, and of Self-Reference, $F_{1, 36} = 7.77$, $p < .01$, $\eta^2_p = .18$, showing negative beta values for both past and future events, with a greater reduction for past as compared to future events (Figure 4, Right). The Self-Projection × Self-Reference interaction, $F_{2, 72} = 4.63$, $p = .01$, $\eta^2_p = .11$, was also significant. Post hoc analysis revealed a lower activation for past than for future events, when participants were projected both in the Future and in the Present (both $p < .05$). Moreover, SFG displayed a significantly lower activation for future events in the Past projection as compared to future events in the Present and Future projections (both $p < .01$).

The analysis on temporal regions in post-PA indicated a significant main effect of Self-Projection, $F_{2, 72} = 3.67$, $p < .05$, $\eta^2_p = .09$, in left STG, with a higher activation in the Present as compared to Future projection, as well as a significant main effect of Self-Reference, $F_{1, 36} = 5.87$, $p = .02$, $\eta^2_p = .14$, with a higher activation for past as compared to future events (Figure 4, Right). On the contrary, in the right hemisphere, right STG did not show any significant effect ($p > .05$).

Overall, these results showed that during post-PA the right IPL is generally involved in the MTT task, the left IPL is more activated when participants projected to the Past, while the left SFG was less activated for future events.

Figure 4 Post-PA Session Functional Results

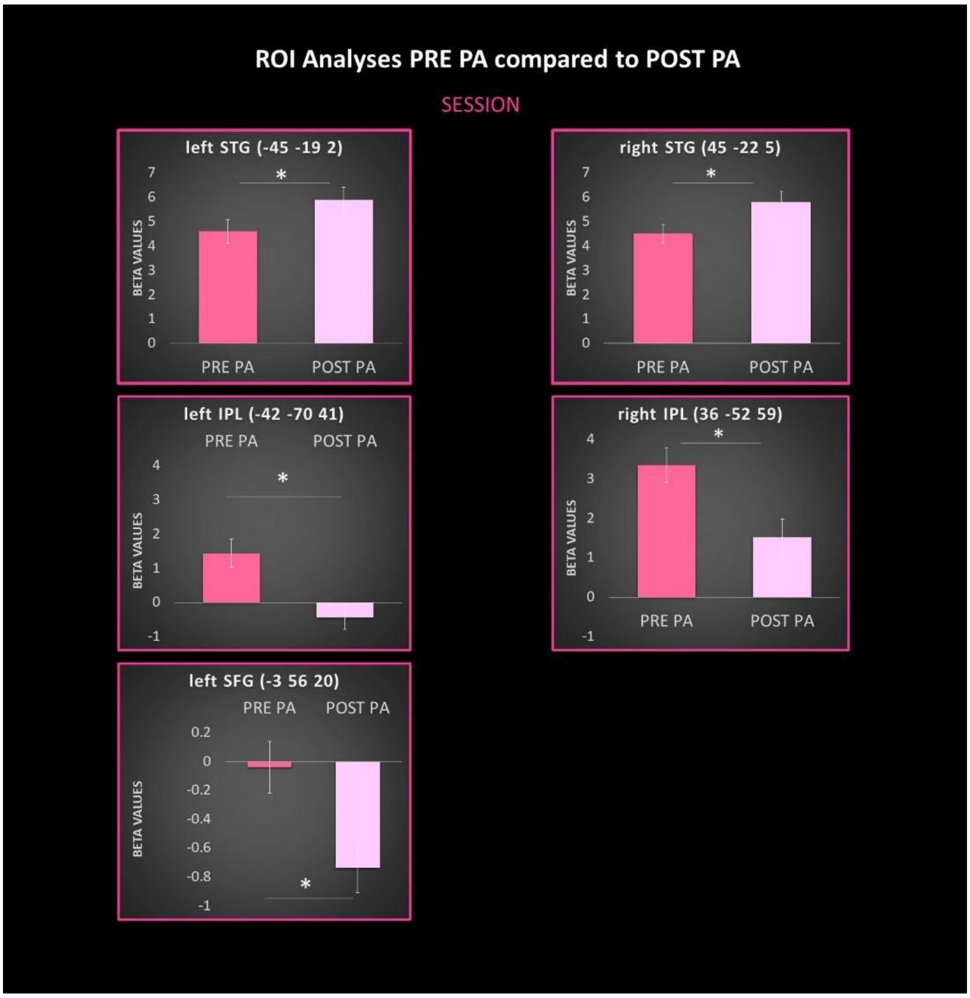


*Note. Left: Activations (yellow blobs) and reductions of activation (blue blobs) in post-PA > pre-PA; cluster size k > 109, corrected at α < .05. Right: Bar plots represent ROI analyses results in the post-PA session as a function of MTT conditions (Self-Reference in green and Self-Projection in red). Error bars depict standard errors of the mean (SEM). ROI = regions of interest; MTT = mental time travel; IPL = inferior parietal lobule; STG = superior temporal gyrus; SFG = superior frontal gyrus; PA = prismatic adaptation. * p < .05.*

ROI Analyses with Session (Pre-PA, Post-PA) as Factor

A significant main effect of Session was found in right IPL, $F_{1, 36} = 25.68$, $p < .001$, $\eta^2_p = .42$, and left IPL, $F_{1, 36} = 28.69$; $p < .001$, $\eta^2_p = .44$, in the ANOVAs conducted with session (pre-PA, post-PA), Self-Projection (Past, Present, Future) and Self-Reference (past, future) as within subjects factors. Both these areas showed a reduced activation in the post-PA session (Figure 5). Results from the analyses of the rest of the ROIs are reported Supplemental Materials.

Figure 5 ROI Analyses Results



Note. *Session main effect in ROI analyses. Error bars depict standard errors of the mean (SEM). ROI = regions of interest; IPL = inferior parietal lobule; STG = superior temporal gyrus; SFG = superior frontal gyrus; PA = prismatic adaptation. * p < .05.*

PPI Analyses

Considering that the effect of PA at behavioral level was limited to past events in Past projection, we conducted PPI analyses evaluating the interaction of this condition with the Blood Oxygenation Level Dependent (BOLD) signal in the right and left IPL.

Right IPL post-PA did not show any significant positive correlation, whereas the connectivity decreased bilaterally with superior and middle temporal gyri, occipital cortices, insula, inferior and middle frontal gyri, and parietal cortices, comprising superior parietal lobule, angular gyrus, and precuneus (Supplemental Table S3).

Left IPL post-PA showed a significant positive correlation with left superior frontal gyrus (Supplemental Table S4), whereas the connectivity decreased bilaterally with superior and middle temporal gyri, occipital cortices, inferior and middle frontal gyri and right inferior and superior parietal lobules, comprising precuneus and angular gyrus, and supplementary motor area (Supplemental Table S5; see also Figure S3).

Discussion

In a single event fMRI protocol, we studied the neural activations during a MTT task before and after a single session of PA inducing a leftward shift of spatial attention. As a consequence of the manipulation of spatial attention, when participants were projected to the Past, the performance for past events improved, and concurrently a modulation of brain activity in the fronto-temporo-parietal network involved in the MTT task was observed. Specifically, bilateral IPL and left SFG reduced their activation, while bilateral STG increased its activation. Consistent with behavioral studies, performance before PA worsened when participants were projected to a time location different from the Present. When participants are asked to imagine themselves in a specific time location (Past, Present or Future), they adopt a first person (egocentric) perspective. Once a given temporal location has been adopted, moving to a different location is achieved by paying a switching cost in remapping their location on the MTL. Hence, this results in a cost on the MTT performance in terms of accuracy and speed (Arzy et al., 2009b; Anelli et al., 2016b; Gauthier and van Wassenhove, 2016).

Beyond this overall effect, participants’ performance worsened in judging future events in the Past projection, and in judging past events in the Future projection. Such effects, here reported for the first time, could be due to an incompatibility between the Self-Projection and Self-Reference temporal directions. Indeed, when these conditions are opposed, a further cognitive effort would be required, not only to imagine oneself in different time locations, but also to orient oneself towards an opposite time direction. This effort may result in higher switching costs occurring when we refer to two different temporal frames.

More interestingly, in the Post-PA session, we found an improvement in responding to past as compared to future events when participants projected themselves to the Past. The same facilitation was also found when comparing past events in Past and Present projection. We interpreted the improvement toward the Past as a selective effect of the leftwards shift of spatial attention induced by PA. This evidence is consistent with the well-known spatial representation of time (Bonato et al., 2012; Magnani et al., 2014, 2021; Anelli et al., 2015, 2016b; Candini et al., 2022). Further support for the interpretation of visuospatial modulations of PA on MTT comes from the finding that exposure to neutral lenses did not change participants' performance (Control Experiment). Compared to the "canonical" prismatic deviating lenses, the neutral goggles do not deviate the visual field. Therefore, the Control Experiment excludes the possibility that the results from the fMRI experiment could be simply explained by spurious effects due to familiarization or task repetition.

On the functional point of view, a widespread bilateral network was activated during the execution of the MTT task before prism exposure, including fronto-parietal areas, parahippocampal cortices, occipital cortices, basal ganglia and cerebellum. Focusing on the regions of interest (ROIs), before PA right and left inferior parietal lobules (IPL) were both recruited: the right IPL was activated in the Future projection, whereas the left IPL was activated during the task irrespectively of conditions. These results are in line with Arzy et al. (2009b), who showed that the BOLD signal changed bilaterally in the posterior parietal cortex (PPC) in Self-Projection conditions, arguing that PPC is implicated in both episodic thinking and spatial representation, thus mediating visual imagery during self- and space-related tasks. Using a different paradigm of MTT and a spatial navigation task, Gauthier and vanWassenhove (2016) found a specific activation of a small region of right IPL (BA 39) both in temporal and spatial Self-Projection. Thus, the authors suggested that this sub-region mediates egocentric mapping, required to mentally travel in time and in space.

Furthermore, the Pre-PA ROI analyses revealed the recruitment of left superior temporal gyrus (STG) and left superior frontal gyrus (SFG), especially for the Self-Reference condition. Notably, left STG showed a higher activation when participants classified past events compared to future events, suggesting that this area is involved in accessing past information. In agreement with this view, several studies showed that the left STG (and particularly BA 22) is recruited to successfully recall names (Yagishita et al., 2008) or images (Wu et al., 2020), disclosing its role in memory-related processing. On the other hand, when participants classified future compared to past events, the left superior frontal gyrus (SFG) activation increased. Previous research has suggested that frontal areas play a pivotal role in anticipating future occurrences and decision-making related to the future (Ciaramelli and Di Pellegrino, 2011; Ciaramelli et al., 2021b). In addition, as argued by Arzy at al. (2009b), the frontal lobe is recruited in the future Self-Reference component of MTT "when transposing one's reference point from self to other, from here to there, and from now to then" (Arzy et al., 2009b). Our results fit nicely with this view, suggesting that the activity of the left SFG facilitates the processing of future events, regardless of the temporal projection (Anelli et al., 2016b). Alternatively, Gauthier and vanWassenhove (2016) proposed that such a frontal region mediates temporal and spatial ordering of memories. Since these two views do not exclude each other, here we hypothesize that SFG is required to give a temporal/spatial order to future events. Summarizing, we suggest that right IPL is involved in the Future projection, whereas both left STG and left SFG are involved in Self-Reference, with a complementary role in judging past and future events, regardless of the projection in time.

Looking at the PA modulations on the MTT-related network, in the Post-PA session we observed changes in bilateral IPL and left SFG activity, as well as a selective enhancement of activation in bilateral STG. Then, focusing on the changes induced by PA on parietal regions, ROI analyses showed reduced activity in both left IPL and right IPL. However, the reduction of the left IPL activity was less evident when participants were asked to project themselves to the Past (Self-Projection), suggesting a spared activation of this for Past projection. Thus, we can speculate that such spared activity may reflect the behavioral improvement following PA found in projecting to the Past. Interestingly, the BOLD signal of right IPL correlated with participants' performance: the lower the activity of right IPL, the worse the performance for future events when participants were projected to the Past. Here, we can speculate that this pattern of functional activity in right IPL may indirectly facilitate the access to past events in Past projection, coherently with the behavioral improvement for past, as compared to future events, in the same projection. Overall, this parietal modulation could explain the unbalanced spatial attention towards the past (left of MTL) as a result of PA. In addition, this pattern is in line with an fMRI study by Crottaz-Herbette et al. (2014) showing that a brief exposure to PA induced a bilateral decrease of activation in IPLs when participants performed visuo-spatial and working memory tasks.

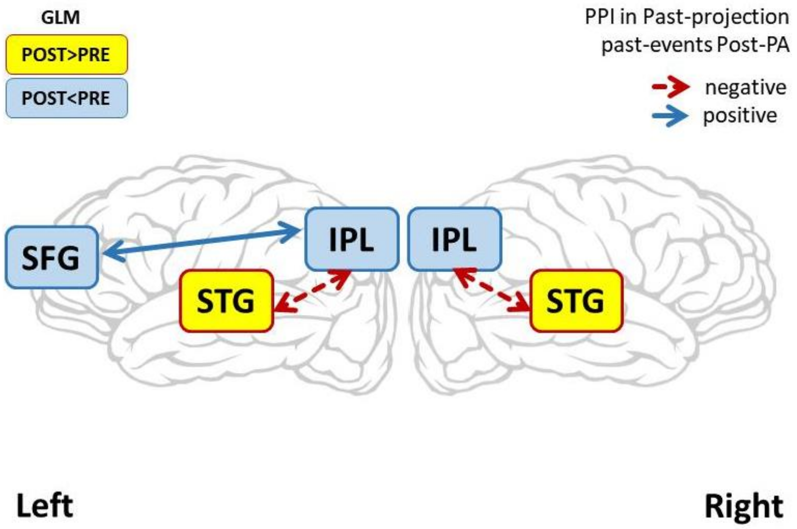
When looking at the prefrontal cortex, ROI analysis showed that in Post-PA session the activation of left SFG was overall reduced. More specifically, left SFG showed a greater reduction of the BOLD signal when participants were projected to the Past than to the Future, and a reduced activation when judging future events, confirming previous neuropsychological evidence of a prefrontal involvement in Future Self-Projection and future Self-Reference (Ciaramelli et al., 2021a; Stendardi et al., 2021). For instance, Ciaramelli and colleagues (2021a) demonstrated that patients with prefrontal injuries were impaired both in projecting themselves to the Future and in judging future events. This deficit was interpreted as an inability to construct future representations in both components of MTT. In light of this view, we can speculate that the decrease of activation in left SFG due to the PA exposure may resemble the future oriented MTT deficit found in patients with prefrontal damage.

Superior temporal regions were also modulated by the exposure to prismatic lenses, with an enhancement of the BOLD signal in bilateral STG in the Post-PA session. Furthermore, ROI analysis indicated that the right STG increased activity was not related to any MTT condition, thus suggesting a role of STG in maintaining the effects induced by the prism exposure. This hypothesis is in line with results obtained by Luauté et al. (2009) in healthy participants, and by Karnath and colleagues (2001) on patients with neglect as well as in transcranial magnetic stimulation (TMS) studies on healthy participants (Shah-Basak et al., 2018). Considering the involvement in MTT, the ROI analysis on left STG confirmed the engagement of this area in the Self-Reference for past compared to future events, not only in Pre but also in Post PA.

Psycho-physiological interaction (PPI) results showed that left and right IPLs were negatively correlated with left and right STGs after PA, as the activation of both IPLs decreased, the activation of both STGs increased. Coherently with our results, Schintu et al. (2020) found that the resting state functional connectivity (RSFC) was reduced between PPCs and STGs bilaterally after PA. Furthermore, Wilf et al. (2019) showed a reduced connectivity of left IPL with right superior temporal regions following a leftward shift of attention induced by PA. The authors claimed that the decoupling between these areas could be the initial core where the attentional bias towards the left side of space takes place. Interestingly, we also found the activity of left IPL positively correlated with left SFG after PA, suggesting another possible pathway of spatial attention modulation on MTT.

Based on our results and on the previous literature, we suggest an anatomo-functional model that should explain the effects of PA on MTT (Fig. 6). A leftward shift of spatial attention following PA induces, at behavioral level, a facilitation of Past Projection and past events and, at neural level, an effect on both IPLs. This, in turn, activates both STGs and inhibits left SFG. More specifically, we propose that the facilitation of Past Projection may be linked to the bilateral modulation of IPLs activity, while the facilitation of past events is mediated by the inhibition of left SFG and by the increased activation of left STG. Finally, the right STG maintains the PA effects.

Figure 6 Anatomo-functional Model



Note. Model of PA effects on an attentional network during MTT when judging past events in Past projection. IPL = inferior parietal lobule; STG = superior temporal gyrus, SFG = superior frontal gyrus. Boxes represent the results of the GLM analysis: POST > PRE = brain areas showing increased activation in the post-PA session compared to the pre-PA (in yellow). POST < PRE = brain areas showing decreased activation in the post-PA session compared to the pre-PA (in light blue). Arrows indicate the results of the psychophysiological interactions (PPI) analysis: dotted arrows (in red) indicate a negative PPI; solid arrow (in blue) indicates a positive PPI. MTT = mental time travel; GLM = general linear model; PPI = psychophysiological interactions; PA = prismatic adaptation.

In conclusion, our findings and the proposed model shed light on the functional role of the brain areas mediating the effects of spatial attention on our ability to project ourselves in time and to judge whether some events already happened or are expected to happen in the future. Moreover, our results have important implications to further understand the mechanisms underlying the improvement of the neglect deficits following PA, where patients' impairments may concern not only the spatial but also the temporal domain. Overall, these findings support the hypothesis of a spatial representation of the subjective timeline. Further work is needed to explore whether such findings following the manipulation of spatial attention on MTT could be also framed within different theoretical models, taking into account other factors mediating the association between time and space.

Before concluding, it is worth noticing some limitations of our study. Firstly, we did not control for the rightward shift of spatial attention. We selected the leftward attentional shift as our focus, given our primary aim to identify the brain structures underpinning the PA effects on MTT in the healthy population as a preliminary step, with the aim to build an anatomo-functional model that will be also tested in patients with left neglect. Nevertheless, further research is necessary to assess the effects on MTT and their neural substrates of the rightward shift of spatial attention in the healthy population and in neuropsychological patients. Another limitation of the present study consists in not considering personal or non-personal categorization of the events as factors in the analyses. Since this is a relevant component in MTT ability, future studies will address this issue investigating the effects of PA on personal and non-personal events. Moreover, we only tested young participants because different age groups may adopt different temporal perspectives when making judgments about the events used in the MTT task. Further research on older adults will be necessary to clarify how aging affects the ability to MTT and its associated functional correlates. Lastly, we would like to point out that this study was conducted with a limited sample of Western participants. Previous research has shown that the representation of time can be influenced by culture, and different effects of PA on MTT have been observed in individuals from diverse cultural backgrounds, particularly those with distinct reading and writing systems (Anelli et al. 2018b). Future research involving a larger sample, including participants from different cultural backgrounds, will be essential for a comprehensive model of the MTT-related neural correlates and their modulation after shift of attention.

Experiment 2

Effects of the Perceived Temporal Distance of events on Mental Time Travel and on its underlying brain circuits.

This study has been published in Casadio C., Patanè I., Candini M., Lui, F., Frassinetti F., Benuzzi F. Effects of the Perceived Temporal Distance of events on Mental Time Travel and on its underlying brain circuits, *Experimental Brain Research,* 2024

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Introduction

Mentally travelling in time (MTT) is the cognitive ability to re-experience past events and imagine future scenarios (Tulving, 1985). MTT enables humans to disengage from the “here and now” spatio-temporal location and to envision past or future episodes. In addition, travelling towards the past relies on episodic autobiographical memory, while projecting towards the future implies episodic future thinking (Dafni-Merom & Arzy, 2020). As proposed in A Theory Of Magnitude (ATOM, Walsh, 2003a, 2003b), time, space, numbers and other magnitudes share mapping metrics, and from this theory a spatial representation of time derives. According to ATOM, at the cognitive level, time is represented along a left-to -right line, known as Mental Time Line (MTL; Scozia et al. 2023; Candini et al., 2022; Patané et al., 2016; Ouellet et al., 2010). Thus, we can mentally travel between past and future, represented on the left and right part of such a line, respectively (Bonato et al., 2012; Oliveri et al., 2009). Adopting this view, two main visuo-spatial components of the MTT can be disentangled. The first one is the self-projection component, which is the ability to change the viewpoint from the present time to different moments of subjective time by moving mentally along the MTL (Buckner & Carroll, 2007). Thus, self-projection mainly relies on a re-mapping of the egocentric point of view to reconstruct the temporal context (Arzy et al., 2008; Gauthier & van Wassenhove, 2016a). Accordingly, being projected in time enables us to change temporal viewpoints relative to a specific event, and this is the self-reference component of the MTT (Arzy, Adi-Japha, et al., 2009b; Arzy, Collette, et al., 2009a; Arzy et al., 2008). As an example, an event which has already happened, such as the Milan Expo (2015) would be considered as a relative-future event if we projected ourselves to ten years ago (i.e., to 2013). Arzy and colleagues (2008) developed a novel task to investigate these so-called chronometric components of MTT. Participants were instructed to project themselves either to the present, to the past (ten years ago) or to the future (in ten years). They were then asked to judge a series of events as either relative-past or relative-future with respect to the adopted time-location. Participants were slower and less accurate in self-projecting to past and future compared to the present location (Arzy, Collette, et al., 2009a; Arzy et al., 2008, 2009a, see also Gauthier & van Wassenhove, 2016a, 2016b). Moreover, the Temporal Distance (TD) behavioural effect was found: the closer the events to the considered time location, the slower the reaction times (RTs). Interestingly, Arzy and colleagues demonstrated that temporal distance contributes to re-mapping events in the adopted temporal self-location during MTT, since the performance changes according to the temporal distance of events with respect to the adopted time location (Arzy, Adi-Japha, et al., 2009b). Gauthier & van Wassenhove (2016a, 2016b) replicated the temporal distance effect by demonstrating that longer RTs and higher error rate (ER) are required when processing close events. This may result from a complex computation due to the event temporal proximity: the mental representation of an event becomes more detailed and time-consuming when the event is closer in time.

At the neural level, the right temporo-parietal junction (TPJ) may contribute to processing the relationship between the participant’s actual self-location in time and the imagined one during the MTT task (Arzy, Collette, et al., 2009a; Arzy et al., 2006; Blanke & Arzy, 2005). Additionally, the right inferior parietal lobule/angular gyrus (IPL/AG; BA 39) and anterior insula participate in judging events as close or far from the participant’s point of view, irrespective of the projection (Gauthier & van Wassenhove, 2016b). Furthermore, the distance effect has been investigated in the numerical domain (van Opstal et al. 2008; Dehaene et al. 2003), revealing a specific involvement of parietal regions in numerical quantity processing, calculations and numerical manipulations, and even in implicit processing of quantities (Dehaene et al. 2003).

It is worth noting that none of the previous studies on the temporal distance effect considered the subjective perception of distances from the participants' point of view. That is, events were a-priori categorised as either close or far (categorical variable), aiming to control for the number of years elapsed from a given event. However, how participants perceived those temporal distances, especially for future personal and non personal events, was not taken into account. Indeed, predictions about future events are expected to vary significantly among individuals, depending on personal background. For example, some participants may perceive the flooding of some Mediterranean islands as imminent in the future due to their knowledge of the extreme effects of climate change, while others may find this event very unlikely to occur. However, the impact of perceived temporal distance (PTD) on performance in temporal tasks, and the specific brain structures mediating this subjective temporal perception have not been previously investigated. Crucially, no previous studies have investigated whether the PTD for relative-past and relative-future events is subtended by the same neurocognitive mechanisms. Assessing whether their neural networks overlap or not can provide insight into the processes involved in the MTT itself.

In the present study, we aim to investigate how the PTD influences the MTT ability and to elucidate the neural correlates of this phenomenon. To achieve this, participants performed an adapted version of the MTT task during a functional Magnetic Resonance Imaging (fMRI) protocol. Then, participants were asked to estimate, in years, the distance of the relative-past and relative-future events employed in the MTT task. To identify the neural basis of the effect of PTD on the MTT ability, we analysed fMRI data as a function of these estimations individually. We expected that the perceived proximity of relative-past and relative-future events in relation to the self-location in time would worsen the performance in the temporal task (Arzy, Adi-Japha, et al., 2009b; Gauthier & van Wassenhove, 2016a). Regarding the functional correlates, we predicted the activation of a widespread network comprising medial frontal, retrosplenial and parietal areas (Arzy, Collette, et al., 2009a;

Gauthier & van Wassenhove, 2016b; Peer et al., 2015). Moreover, we expected the functional involvement of a temporo-parietal network in the perceived temporal distance processing, irrespective of whether the events were relative-past or relative-future. Specifically, we predicted that this “PTD’s core network” would include IPL/AG and TPJ (Arzy, Collette, et al., 2009a; Gauthier & van Wassenhove, 2016b). In addition to this and specifically for relative-future events, we expected the involvement of brain regions engaged in imaginative and constructive processes (Addis, 2007).

Materials and methods

Participants

Thirty-three right-handed (Oldfield, 1971) healthy volunteers (20 females and 13 males; mean age 24.9 ± SD 2.5) took part in the experiment. We recruited a sample as homogeneous as possible to reduce interindividual differences in the MTT task related to the succession of events in participants’ life. All participants provided written informed consents, in accordance with the local ethics committee (Comitato Etico dell’Area Vasta Emilia Nord – Authorization code number: CE 134/2014/SPER/AOUMO) and the Declaration of Helsinki (2013).

Procedure

Participants performed an adapted version of the Mental Time Travel task (Casadio et al., 2023; Anelli et al., 2016a), arranged in a jittered single event fMRI protocol. Before entering the scanner for the experimental session, participants were provided with the list of stimuli, so that they could familiarise with the events, in order to avoid any novelty effect during functional data acquisition. The functional session consisted in two acquisition runs of 36 trials each. At the beginning and at the end of each run, 20 seconds of fixation were introduced to record a baseline for the fMRI signal. A custom-made software developed in our laboratory (http://digilander.libero.it/marco_serafini/stimoli_video/) was used for stimuli presentation via the ESys System (http://www.invivocorp.com) remote display, and for behavioural data collection.

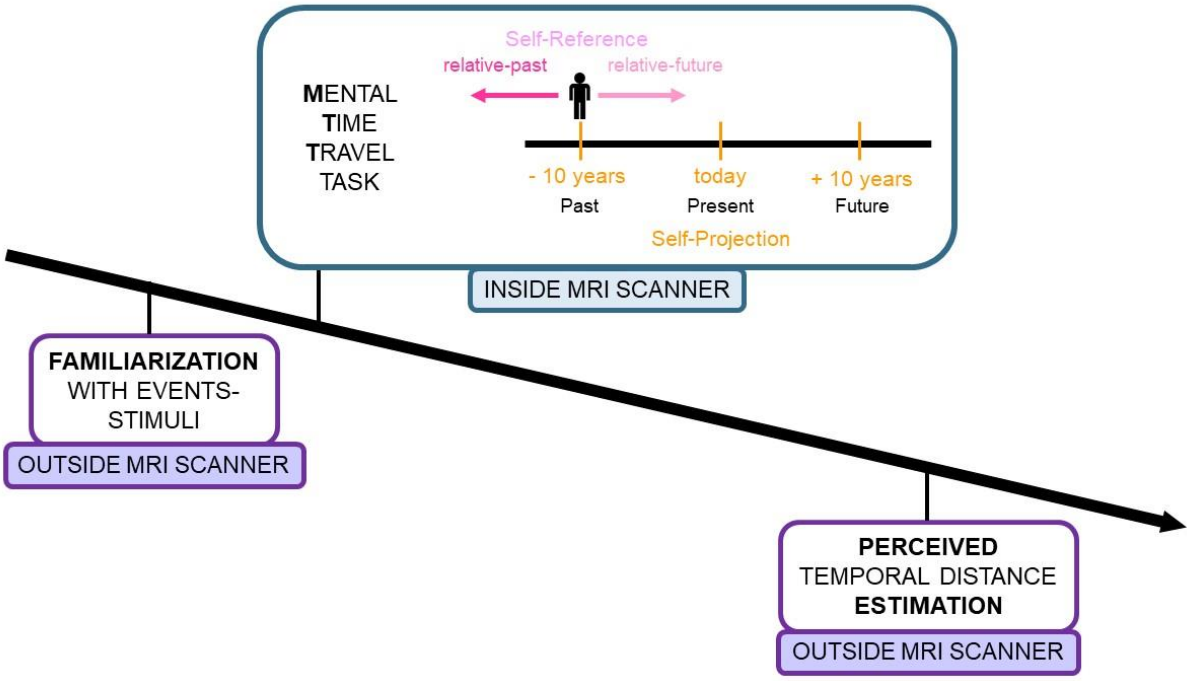
The trial started with a visual warning signal (a blue screen), lasting 500 ms. During the MTT task, the written instructions about the Self-Projection condition appeared on the screen, asking participants to imagine themselves either in the Present (today), or in the Past (ten years ago), or in the Future (in ten years). Instructions were displayed for the entire duration of the trial. 500 ms after the instructions had appeared, stimuli started. Stimuli were auditory two-word descriptions of events, lasting 2000 ms and delivered through MRI compatible headphones. Events were chosen and adapted from a validated list (Supplementary Information Table 1; see also Anelli et al., 2016b). The presentation order of events was pseudo-randomised as a function of the Self-Projection and the Self-Reference condition, resulting in five different sequences of events presented in the task. We chose this approach to control for a possible order effect on the MTT performance. Participants had to classify each event as either "past" -i.e., "occurred before"- or "future" -i.e., "occurred after"- (Self-Reference conditions) with respect to the location in time requested by the Self-Projection instruction. Participants had to respond within a 2000 ms temporal window once the audio was finished. Thus, six experimental conditions were obtained from the combination of Self-Projection (3) and Self-Reference (2):

- Past – relative-past;
- Past – relative-future;
- Present – relative-past;
- Present – relative-future;
- Future – relative-past;
- Future – relative-future.

From now on, we will refer to the Self-Projection conditions using capital letters, i.e., Past, Present and Future, while we will refer to the Self-Reference conditions using the terms "relative-past" and "relative-future".

Participants responded by pressing a two-button keypad either with their index or their middle finger, as quickly and precisely as possible (Fig. 1). In order to avoid motor facilitation due to the spatial representation of time, the responding associations were counterbalanced within participants: half of the participants responded “past” with the index finger and “future” with the middle finger, and the other half used the opposite association. RTs and accuracy were recorded. The inter-stimulus intervals were pseudo-randomised (range 0.5 - 19.7s) using the make_random_timing.py script from the AFNI package (https://afni.nimh.nih.gov/).

Figure 1 Experimental timeline



Note. At the beginning of the experimental session, outside the MRI scanner participants familiarised with the stimuli reading the list of the events. Then inside the MRI scanner, participants performed the MTT task, as illustrated in the box. Once the fMRI data collection finished, outside the MRI scanner participants provided their own personal temporal distance estimates for each event of the task

Functional data acquisition

Functional volumes were acquired on a 3T GE Signa Architect system, each of the two runs comprising 320 volumes, each including 46, 3-mm-thick slices (TR= 1500 ms, TE= 30 ms, voxel size 3x3x3 mm, gap 0.3 mm, FOV 24x24, matrix 128x128). A high-resolution T1-weighted 3D anatomical image (TR= 2184.9 ms, TE= 3 ms, 46 slices, voxel size 1x1x1 mm) was collected for each participant to allow anatomical localization.

Data analysis

Behavioural data

Pearson's correlations were conducted between mean absolute values of PTD, calculated across trials, and behavioural performance in each MTT condition, indexed by mean RTs or mean accuracy (percentage of correct answers). Additionally, a series of correlations were computed between mean absolute values of PTD and mean RTs or mean accuracy for each Self-Reference condition, collapsing Self-Projection. To test the causal relation between PTD and behavioural performance we used the individual regression equations method on RTs, as suggested by Lorch and Myers (1990), Bonato et al. (2007) and Pinhas et al. (2012). We ran a single regression analysis for each participant in each MTT condition: mean RTs served as the dependent variable, and the mean absolute values of PTD as the predictor. Then, we performed a series of one tailed t-test against zero on the betas obtained for each participant in each MTT condition.

Functional data

MatLab R2020a (MathWorks, 2020) and SPM12 software (Wellcome Trust Centre for Neuroimaging, http://www.fil.ion.ucl.ac.uk/spm/) were used for functional data analysis. The following pre-processing steps were run: slice-timing, spatial realignment, normalisation to the MNI template and smoothing with 6 mm full width Gaussian filter. A two-level analysis was implemented. A single-subject statistical analysis was performed applying the General Linear Model (GLM), where the time-series data were modelled as a series of events convolved with a canonical hemodynamic response function. The regressors of interest were as many as the combinations of factors, i.e., the experimental conditions. Motor response, errors, and head-motion parameters (translations and rotations) were entered as nuisance variables. In this single-subject statistical analysis, each individual

PTD value was entered as parametric factor matching with its corresponding event of the task (i.e., a single estimated temporal value for each MTT trial). The relationship between brain activity (Blood Oxygenation Level Dependent, BOLD signal) and PTD was modelled with first (linear) polynomial order function. Regressors of interest were as many as the first order functions of each experimental condition (six regressors). The individual contrast images were entered into whole brain analysis at group level and a full-factorial ANOVA with Self-Projection (Past, Present, Future) and Self-Reference (relative-past, relative-future) as factors was conducted for first order relationships. The following contrasts were considered in each analysis (first order relationship):

- Past – relative-past > baseline
- Past – relative-future > baseline
- Present – relative-past > baseline
- Present – relative-future > baseline
- Future – relative-past > baseline
- Future – relative-future > baseline
- Past_projection > baseline
- Present_projection > baseline
- Future_projection > baseline
- relative-past > baseline
- relative-future > baseline.

Both positive (contrast weight +1) and negative (contrast weight -1) relationships were investigated for all the contrasts.

To further explore our dataset, we compared the results from the parametric analysis investigating the PTD effect with those coming from MTT analyses (see Supplementary Information). We masked exclusively the contrast relative-past > baseline in the parametric analysis (i.e., the brain areas which increased their activity for close relative-past events - PTD) with the contrast relative-past > baseline from the MTT analysis (i.e., the brain areas activated when responding to relative-past events). We also masked exclusively the contrast relative-future > baseline in the parametric analysis (i.e., the brain areas which increased their activity for close future events - PTD) with the contrast relative-future > baseline from the MTT analysis (i.e., the brain areas activated when responding to future events).

Given our hypothesis that PTD and RTs are related, we aimed to rule out the possibility that the brain activity possibly associated with the PTD effect may be due to an unspecific time on task effect (i.e., longer RTs), we conducted a parametric analysis on our functional data with RTs (and not PTDs) as parametric factors. If different brain regions were found significantly related to the RTs in the BOLD signal, this would confirm that the activations found as a function of PTDs are specific for the PTD effect, regardless of the time on task. As in previous analyses, a dual statistical threshold was applied to obtain a combined significance level corrected for multiple comparisons ($\alpha < 0.05$), as computed by the 3dClustSim AFNI routine using the "-acf" option, and the minimum cluster size for the parametric modulation analysis was 69 voxels.

An additional analysis was conducted with the same first and second level parameters of the parametric analysis on PTDs, adding the factor "type of events", i.e., either personal or public. The following contrasts were considered:

- personal– relative-past > baseline;
- personal – relative-future > baseline;
- public – relative-past > baseline;
- public– relative-future > baseline;
- personal– relative-past > public– relative-past;
- public– relative-past > personal– relative-past;
- personal– relative-future > public– relative-future;
- public– relative-future > personal– relative-future;

- personal_events > public_events;
- public_events > personal_events.

We addressed this issue since a “personal vs public” effect is known to affect the MTT performance: shorter RTs and greater accuracy when responding to personal as compared to public events have been reported (Anelli et al., 2016a, 2016b; Arzy, Collette, et al., 2009a; Arzy et al., 2008).

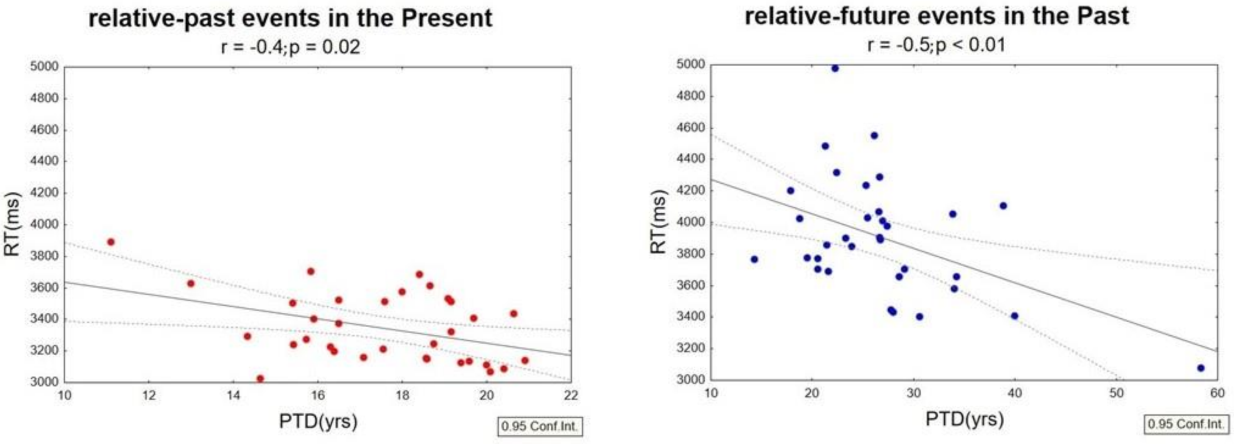
A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of α<0.05, as computed by 3dClustSim AFNI routine, using the “-acf” option (https://afni.nimh.nih.gov/pub/dist/doc/program_help/3dClustSim.html). The minimum cluster size for the parametric modulation analysis was 37 voxels.

Results

Behavioural results

We found negative correlations between PTDs (absolute value) and RTs both for relative-past events in the Present Self-Projection condition (r = -0.4, p = .02, Fig. 2, left) and for relative-future events in the Past Self-Projection condition (r = -0.5, p < .01, Fig. 2, right). Thus, the closer the events (past and future) the slower the performance. Pearson's analyses between PTDs and accuracy showed a positive correlation for relative-past events in the Present Self-Projection condition (r = 0.5, p < .01, Supplementary Fig. 1): the closer the past events are to the Present, the less accurate the performance. When considering only the Self-Reference component regardless of the Self-Projection condition, PTDs and accuracy for relative-past events were positively correlated (r = 0.5, p < .01, Supplementary Fig. 2), suggesting that the closer the past events, the less accurate the performance. No other significant correlation was found (for detailed results on the MTT task see Supplementary materials). The individual regression equations analysis revealed that the averaged negative slopes of the relative-past events in the Past (-0.11 ms; *t* (32) = -2.76; p < .01), relative-future events in the Past (-0.27 ms; *t* (32) = -5.01; p < .001) and of the relative-past events in the Present (-0.10 ms; *t* (32) = -1.91; p = .03) significantly deviated from zero. In addition, also the averaged negative slopes of the overall relative-past events (-0.09 ms; *t* (32) = -3.11; p < .01) and overall relative-future events (-0.08 ms; *t* (32) = -2.46; p < .01) were significantly different from zero. This confirms that the closer the events, the slower the performance.

Figure 2 Behavioural results



Note. Mean RTs as a function of mean PTD for relative-past events (absolute value) in the Present self-projection condition (graph on the left) and for relative-future events in the Past self-projection condition (graph on the right).

Functional results

The parametric analysis showed significant linear relationships for relative-past and relative-future Self-Reference conditions (i.e., relative-past > baseline; relative-future > baseline). In particular, PTD for relative-past events (expressed in negative values) showed a positive significant relationship (contrast weight +1) with fMRI signal in several areas, namely, bilaterally in middle and superior medial frontal gyri, cingulate cortex, retrosplenial cortex (precuneus, cuneus), supramarginal and angular (AG) gyri, middle and superior temporal gyri, including temporo-parietal junction (as identified in x= 47.5 ± 0.5, y= -61.5 ± 3.5, z= 20.5 ± 4.5; Geng & Vossel, 2013), and in left superior and inferior parietal lobule (IPL), precentral gyrus and pre-supplementary motor area (Table 1 and Fig. 3). PTD for relative-future events showed a negative significant relationship (contrast weight -1) in a strikingly similar pattern of brain areas, with minor differences in peak coordinates and extent (Table 2 and Fig. 3). Hence, the closer the PTD for relative-past and relative-future events, regardless of the Self-Projection condition, the more these brain areas are involved. In addition, relative-future events also showed a specific negative linear relationship in left lingual and parahippocampal gyri and right cerebellum (Table 2).

Table 1 Results of the linear relationship with PTD for relative-past events

Anatomical regions	**BA**	**Side**	**Cluster**	**Voxel level**	**MNI coordinates**		
			K	***T***	***x***	***y***	***z***
Cingulate Gyrus, Precuneus	23, 30, 31, 7	*r*	132	5.74	3	-52	26
Middle and Superior Frontal Gyrus, Supplementary Motor Area, Precentral Gyrus	6, 8, 4	*l*	190	5.68	-24	26	47
Middle and Superior Frontal Gyrus	8	*r*	45	4.97	24	20	44
Angular Gyrus (AG), Supramarginal Gyrus, Inferior Parietal Lobule (IPL), Middle Temporal Gyrus	39, 40, 22	*l*	139	4.62	-51	-61	29
Angular Gyrus (AG), Supramarginal Gyrus, Inferior and Superior Temporal Gyrus, Temporo-Parietal Junction (TPJ)	39, 40, 19, 7	*r*	131	4.54	45	-55	23
Superior Frontal Gyrus, Anterior Cingulate	9, 10	*l*	43	3.90	-3	59	14

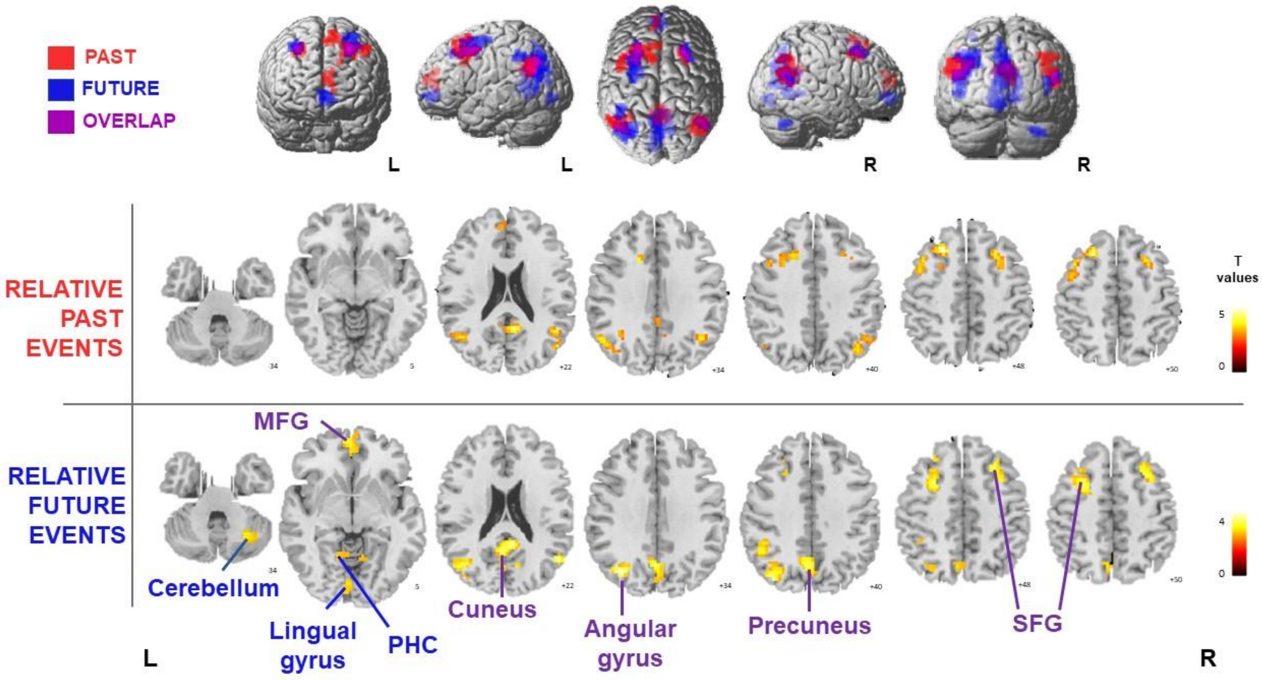
Note. Areas of significant changes in fMRI signal as a function of PTD for relative-past events; BA = Brodmann area; L = left; R = right. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of $\alpha < 0.05$ *(*$p < 0.001$*,* $k > 37$ *voxels)*

Table 2 Results of the linear relationship with PTD for relative-future events

Anatomical regions	**BA**	**Side**	**Cluster**	**Voxel level**	**MNI coordinates**		
			K	***T***	***x***	***y***	***z***
Middle Temporal Gyrus, Angular Gyrus (AG), Precuneus, Superior and Inferior Parietal Lobule (IPL)	22, 39, 7, 30, 19	*l*	204	4.95	-36	-70	35
Superior and Middle Temporal Gyrus, Angular Gyrus (AG), Temporo-Parietal Junction (TPJ)	22, 39	*r*	57	4.71	51	-64	23
Precuneus, Posterior Cingulate, Cuneus, Lingual Gyrus, Parahippocampal Gyrus	30, 31, 23,18, 19, 7	*l*	465	4.58	-6	-52	11
Middle and Superior Frontal Gyrus, Precentral Gyrus	6, 8	*l*	171	4.26	-27	8	47
Middle and Superior Frontal Gyrus	6, 8	*r*	53	4.20	30	17	50
Superior Frontal Gyrus, Anterior Cingulate	10, 11, 32	*l*	60	4.10	-6	56	-4
Cerebellum		*r*	42	3.88	27	-64	-31
Inferior Parietal Lobule (IPL), Supramarginal Gyrus	40	*l*	42	3.82	-48	-52	41
Lingual Gyrus	18	*l*	39	3.62	-6	-82	-7

Note. Areas of significant changes in fMRI signal as a function of PTD for relative-future events; BA = Brodmann area; L = left; R = right. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of $\alpha < 0.05$ *(*$p < 0.001$*,* $k > 37$ *voxels)*

Figure 3 Parametric analysis results



Note. In red the brain areas linearly related with PTDs for relative-past events, in blue the brain areas linearly related with PTDs for relative-future events, purple represents the areas of overlap between the two maps. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of $\alpha < 0.05$ *(*$p < 0.001$ *and cluster size threshold* $k > 37$ *voxels). MFG= Middle Frontal Gyrus; SFG= Superior Frontal Gyrus; PHC= Parahippocampal gyrus; L= left; R= right. Functional results are shown on the SPM12 template; color bars represent T-values*

The masking procedure to identify the brain areas within the MTT network specifically activated as a function of PTD for relative-past events showed the involvement of left superior frontal gyrus (BA 9, 10), right posterior cingulate (BA 23), precuneus (BA 31), bilateral inferior parietal lobule, comprising angular and supramarginal gyri (BA 39, 40), bilateral middle and superior frontal gyrus (BA 6, 8). The same masking procedure for relative-future events revealed the involvement of left medial frontal gyrus (BA 10, 11), anterior cingulate gyrus, angular gyrus (BA 39), middle temporal gyrus (BA 22), precuneus (BA 31), and right superior temporal gyrus (BA 22) and superior frontal gyrus (BA 8). Overall, this explorative analysis seems to highlight a network somewhat similar to the one already revealed from the parametric analysis, further confirming the involvement of these areas in computing the PTD, even when ruling out the MTT related brain activity.

Results of the parametric analysis with RTs as factor revealed significant positive linear relationships between RTs and activity in the left supplementary motor area and bilateral insular cortices both for relative-past and relative-future events (see Supplementary Fig. 3 and Supplementary Tables 2 and 3). Notably, these regions differed from those found in the PTD parametric analysis, allowing us to infer that only these brain regions reflect time on task, whereas the brain activations described in the previous analysis are specifically associated with the PTD effect.

When exploring the potential effect of personal vs public events, by adding the “type of event” as a factor in the parametric analysis, we did not find any significant results. This suggests that the type of event (personal vs public) did not explain the brain activity when considering the PTD.

Discussion

In the present study we investigated how the perceived temporal distance (PTD) of events can affect the Mental Time Travel (MTT) ability and the subtending neural activations. We systematically compared the PTD effect for relative-past and relative-future events in a continuous manner, based on participants' estimated PTDs, and we analysed the BOLD signal changes as a function of these estimates. Our results showed that reaction time (RTs) and accuracy are linearly related to PTDs for relative-past events in the Present and for relative-future events in the Past. This finding suggests that, even without explicit instructions, participants implicitly represent the temporal distance of events while performing the task. It is noteworthy that the relative-past events in the Present and the relative-future events in the Past can represent the same “segment” of the putative Mental Time Line (MTL). Within this segment, the spatial representation of Past influences event processing, including the PTD effect on RTs, based on the self-location adopted in time (resulting in a similar effect for relative-past events in the Present and relative-future events in the Past). Moreover, PTDs correlate with the accuracy for relative-past events in the Present and the accuracy for the relative-past Self-Reference, regardless of the Self-Projection condition. These results suggest that the PTD effect we observed is stronger for the past: the closer the past events, the slower and less accurate the performance. The regression analyses revealed a distance effect for PTDs in relative-past and relative-future events in the Past, as well as in relative-past events in the Present. This effect persisted for both relative-past and relative-future events when collapsing the Self-Projection conditions. Overall, these findings indicate that a decrease in PTDs results in an increase in RTs, i.e., the closer the events, the slower the reaction time, suggesting a causal linear effect of PTDs on RTs. In previous literature, the distance effect is usually taken as evidence for a continuous representation of magnitudes (Pinhas, et al. 2012), which in our case refers to the representation of PTDs on the MTL. Considering previous studies which focused on a-priori dichotomous categorization to study the effect of temporal distance in MTT, our contribution to the MTT literature is especially valuable. Indeed, in the current experiment, PTDs provided by participants did not reproduce a dichotomic evaluation of distances but showed a continuous distribution. Notably, we suggest that these PTDs, rather than the a-priori dichotomic categorization, represent a better predictor of the MTT performance.

It could be pointed out that we did not find the same temporal distance effect for the Future as in previous works (Arzy, Adi-Japha, et al., 2009b; Gauthier & van Wassenhove, 2016a, 2016b). This difference could be ascribed to methodological differences between previous studies and the current one. In those earlier works the authors provided participants with the exact date (in terms of years) of the relative-future events that participants had to retrieve when executing the task. In our task, instead, participants had to implicitly estimate the date of each future event which was not a-priori established. If the exact date for relative-past events is already stored in the long term memory and the order of such events are well established on MTL, this is not the case for relative-future events. This difference is crucial and could have masked the perceived temporal distance effect related to the Future, suggesting dedicated mechanisms involved in future MTT. Indeed, to estimate PTDs of future events, cognitive functions, such as anticipation, simulation, mental imagery as well as scene construction processes, are involved. Hence, the heterogeneity of these processes may have prevented the emergence of a future-related temporal distance effect. Anyhow, future research is needed to verify this intriguing hypothesis.

From a neurocognitive perspective, perceiving events as closer results in longer RTs during the MTT task, owing to the activation of more complex representations, i.e., representations rich in episodic and semantic details, which require longer time to be recalled or imagined. Such complexity level decreases as the chronological distance from the present increases (D'Argembeau and Van der Linden, 2004). These detailed cognitive representations are tied to considerable brain activity, predominantly in the medial temporal lobe. The hippocampus retrieves and integrates an array of memory details, including sensations, emotions, spatial and contextual details (D'Argembeau, 2020), as well as their temporal order (Gauthier, et al. 2020). In particular, the anterior and posterior regions of the hippocampus display different involvement depending upon the detail level, following a gradient from coarse (anterior) to fine details (posterior). In addition, the hippocampus combines segmented information from primary sensory regions and builds event models in the posteromedial cortex (precuneus and posterior cingulate/ retrosplenial cortices) and angular gyrus (D'Argembeau, 2020). Finally, it works alongside parietal areas, particularly inferior parietal cortices, contributing to the vividness of memory recall and allocating attention during this process (Ciaramelli et al., 2008; Cabeza, et al. 2008). The complexity of representations is also related to their spatial, temporal or interpersonal distance. According to the Construal Level Theory by Trope and Liberman (2003), closer objects, including events, are represented more concretely and through more detailed "low-level construals", including specific knowledge, as well as contextual features. This contrasts with more distant events, which are represented more abstractly. From this perspective, the concrete representations tied to proximate events are associated with heightened activity in the anterior and dorsal regions of the medial prefrontal cortex.

The PTD effect here reported is similar to the distance effect observed in the numerical domain (Moyer & Landauer, 1967), besides in other temporal tasks (Bonato et al., 2016). The existence of a common mechanism for quantities and distances estimation, be they spatial, temporal, or numerical in nature, has been already suggested, and it implies that the closer an item is to a certain point of reference, the longer it takes to determine the correct answer (for a review see Bonato et al. 2012). In the temporal domain, Bonato and colleagues (2016) observed that right brain damaged patients with left neglect were also impaired in ordering events in time: they exhibited slower responses to items that occurred before the temporal reference provided in the experimental manipulation. Their finding adds further evidence of a common origin of the spatial effects characterising both the numerical and temporal representations of order. In the numerical domain, this distance effect is typically observed in magnitude judgement tasks, where responses become progressively slower and less accurate as the numerical difference between two numbers decreases. van Dijck and Doricchi (2019) demonstrated an asymmetrical numerical distance effect in right brain damaged patients with left spatial neglect. These patients were abnormally slow only when responding to the closest smaller number as compared to the referential number (i.e., 4 when reference is 5). However, patients with spatial neglect showed a normal SNARC effect (Spatial-Numerical Association of Response Codes, i.e., automatic response association between small/large numbers presented on left/right space, respectively - Dehaene et al., 1993), and performed well in parity judgements ("2 is an odd or an even number?"). In the light of this, van Dijck & Doricchi (2019) proposed that spatial neglect does not affect the spatial coded response selection. Namely, the parity judgments can be solved by activating over-learned representation of numbers on the Mental Number Line. Building on this hypothesis, the perceived temporal distance effect reported in this study for the past could rely on an "over-learned" or "well-stored" representation of temporal orders on the MTL, allowing the PTD effect to emerge. Conversely, the lack of defined knowledge about the future could lead to an "interference" of the envision processes of possible scenarios, affecting (or abolishing) the spatialization of the temporal order of relative-future events and, consequently, the PTD effect in the Future.

To the best of our knowledge, our study represents the first attempt to systematically evaluate the modelling effect of PTDs on the BOLD signal in a continuous manner. We found that the perceived proximity of relative-past and relative-future events is associated with the activation of a shared network, encompassing bilateral angular gyrus, temporal and parietal areas, which include the temporo-parietal junction (TPJ, Geng et al. 2013), retrosplenial cortex, middle and superior frontal gyri. Our subsequent parametric analysis incorporating RTs as factors confirmed that the activations observed as a function of PTDs are indeed specific to the PTD effect and not influenced by an unspecified time-on-task effect, as other distinct regions are linearly related to the RTs.

Regardless of the specific task employed, a “core network” mediating both the retrieval of relative-past and the envisioning of relative-future events has been described, comprising brain areas very similar to those reported in our results (Arzy, Collette, et al., 2009a; Benoit & Schacter, 2015; Hassabis & Maguire, 2007). This aligns with the recent proposal by Addis (2021) of a single “simulation system”. Notably, our findings revealed the involvement of these areas regardless of whether the events were judged as “past” or “future”. This supports our prediction of a “PTD core network” activated for the processing of perceived temporal distances, especially involving TPJ, inferior parietal lobule, angular gyrus, frontal and posterior areas. This is consistent with Arzy, Collette et al. (2009), who identified TPJ as a key structure for the encoding of the self in both the temporal and in the spatial domain. It also aligns with Parkinson and colleagues (2014), who demonstrated that the representations of egocentric spatial, temporal and social distances converge in right TPJ, which is involved in the self-other distinction and in the mental representation of space and events along the Mental Time Line. In addition, Gauthier and van Wassenhove (2016b) found a common representation of distances in right IPL/AG and anterior insula both for the temporal and the spatial domains. Right IPL is identified as a pivotal area for egocentric re-mapping and computation of distances in both domains, as well as for the perception of temporal order. Consistently with these findings, Peer et al. (2015) tested distances (close vs far) in time, space and personal relationship domains, and demonstrated a common activation in the precuneus, IPL, and medial prefrontal cortex. This activation was explained by the processing of the distance between the self-location and the cued stimulus. This observation aligns with the numerical literature, which highlights the crucial role of the posterior parietal cortex, specifically the intraparietal sulcus and angular gyrus, in numerical representations and manipulations. Notably, the left angular gyrus’ involvement in number processing may be linked to the linguistic foundation of arithmetic computations (Dehaene et al., 2003). As this region is also involved in various visuospatial tasks, including eye and/or attention orienting, mental rotation, and spatial working memory, it was identified as a "common ground" for both numerical and spatial domains (Dehaene et al., 2003). Thus, the posterior parietal cortex could also bind numerical and temporal domains.

Our results showed that the brain areas mediating the perceived temporal distance for relative-past and relative-future events do not overlap entirely. This suggests that some of the involved processes could differ, in agreement both with previous literature and with our predictions. It is worth noting that the brain network associated with PTD partly overlaps the Default Mode Network (DMN), which is known to be involved in the self-referential and internal processing (Buckner & Carroll, 2007) and in mental travel, allowing for the change of the mental location of the self and the reorganisation of one's surroundings (Hayman & Arzy, 2021). Notably, two subsystems were identified within the core network of the DMN (Addis, et al. 2009). The first is the remembering subsystem, activated only during the retrieval of detailed past events (i.e., hippocampus, parahippocampal gyrus and widespread regions of posterior visual cortex; Gaesser & Addis, 2011; Thakral et al., 2017). The second is the imagining subsystem, active when envisioning future scenarios (i.e., anterior hippocampus and widespread medial prefrontal and parietal regions; Addis et al. 2007, 2009). Furthermore, neuropsychological studies revealed that right-brain damaged patients exhibiting left neglect were slower when responding to relative-future than to relative-past events, owing to their spatial working memory deficit (Anelli et al., 2018). Additionally, patients with lesions in the ventro-medial prefrontal cortex were specifically impaired when projecting themselves towards the future and when judging the future location of events on the MTL (Ciaramelli et al., 2021). Furthermore, it has been reported the case of a patient whose gray matter volume reduction in thalamus, fusiform gyri and cerebellum bilaterally, was related to his retrograde amnesia, but also with his impairment in envisioning future events (De Luca et al., 2018). Interestingly, we found that the perceived proximity of relative-future events engages left parahippocampal and lingual gyri and right cerebellum. This is in line with our hypothesis of an additional involvement of processes, such as attention, visual imagery and cognitive resources, in constructing possible future scenarios, when ordering events on the MTL.

The parahippocampal cortex (PHC) is implicated in autobiographical memory retrieval, prospection, navigation, theory of mind and Mental Time Travel (Hayman & Arzy, 2021; Spreng et al., 2009). Recent studies suggest that PHC also plays a role in constructing scenarios that are alternative to reality (DiNicola et al., 2023). In this regard, Irish and colleagues (2015) found that the gray matter volume of PHC correlates with the ability to construct spatially coherent scenes, contributing to the processing of spatial and contextual associations. Moreover, Epstein and colleagues (2003) demonstrated that the parahippocampal place area (PPA) enables the computation of the location and the orientation of the self with respect to the internal map. In our results, PHC could mediate the representation of future scenes based on the temporal distance of events, envisioning them in spatial terms relative to the location of the self.

Together with the hippocampal and parahippocampal gyri, the lingual gyrus has been identified as a key region mediating creativity and divergent thinking (Dietrich, 2004; Gilbert, 2001). Namely, Jung et al. (2010) observed that the thinner the gray matter volume of the lingual gyrus, the lower the scores in divergent thinking tasks, particularly in the ideational fluency (i.e., the quantity of original ideas provided). Expanding on these findings, Zhang et al. (2016) demonstrated that a larger volume of the lingual gyrus is associated with increased creativity, as well as with enhanced cognitive flexibility. Furthermore, Zhang and colleagues (2014) highlighted the involvement of the left lingual gyrus in processing relevant visual imagery during the generation of inventive ideas. Additionally, research by Slotnick and Schacter (2006) revealed that the left lingual gyrus plays a role in spatially specific memory processes, implicitly encoding spatial information related to stimuli positioned on the right portion of the screen. Our results could combine all the presented roles of this brain area in the generative process of envisioning future scenarios, since divergent thinking involves retrieving knowledge from memory to creatively organise mental representation as a new idea (Zhang et al., 2020). We speculate that the left lingual gyrus may engage in spatially memory processes to create original future scenarios (located on the right portion of the Mental Time Line), particularly when an implicit representation of the temporal distance of perceived events is considered, as in the MTT task. Functional MRI studies revealed increased activations in the cerebellum during the processing and the construction of future events (Addis et al. 2007), during episodic future thinking (Szpunar et al., 2006), and when predicting future action sequences during mentalizing tasks (Van Overwalle et al., 2022). Interestingly, Oliveri and colleagues (2009) found that repetitive Transcranial Magnetic Stimulation (TMS) on the right cerebellum of healthy participants affected their speed in responding to the future tense of action verbs. In addition, these authors proposed a right cerebellar-left motor brain network involved in anticipating future events (Oliveri, et al. 2009). This hypothesis was confirmed by neuropsychological evidence from patients with cerebellar lesions, whose ability to predict, anticipate and reconstruct sequences of events was impaired (Leggio & Molinari, 2015). Furthermore, the functional connectivity between the cerebellum and the mentalizing network (i.e., angular gyrus, parahippocampal gyrus, lateral occipital cortex, middle temporal gyrus and precuneus) was altered in patients with the behavioural variant of Fronto-Temporal Dementia with deficits in social behaviour (Olivito et al., 2022). This evidence strongly supports the role of the cerebellum in generating alternative scenarios based on internal models or past experiences (Oliveri et al., 2009; Schacter et al., 2007). Additionally, our findings suggest the involvement of the right cerebellum in constructing the future temporal location and anticipating relative-future events in the context of the MTT task, especially in relation to the perception of temporal distances. It is plausible that activation of the right cerebellum may facilitate collaboration among brain areas within the PTD core network. This collaboration could be crucial for generating original future scenarios, involving the lingual gyrus for visual processing and PHC for adopting a different spatial perspective. Nonetheless, future research is needed to test the model we propose here, better exploring the co-activation pattern and the connectivity between these regions.

Our findings assume added significance when considered in the context of the hypothesis by Gauthier and van Wassenhove's (2016b), who proposed that the brain distinctly represents temporal and spatial egocentric distances, as evidenced by the activation of an extensive network specific for the spatial representation of proximity. This network comprised the precuneus/retrosplenial cortex and superior parietal lobule, inferior parietal sulcus, right superior frontal cortex, pre–supplementary motor area, rostrolateral prefrontal cortex, inferior temporal and parahippocampal cortices and left cerebellum. Our study revealed a strikingly similar neural network, however here this network is involved in processing perceived temporal distances. Using both temporal and spatial tasks, Gauthier and van Wassenhove (2016a, 2016b) instructed participants to memorise various details about the events, therefore their temporal task did not involve a spatial component, which was instead prevalent in our study. It is to be noted that the projection of the self and the localisation of the events on the MTL in the current study were executed "on-line" for the first time when participants were tested, whereas temporal locations were provided before executing the tasks in Gauthier and van Wassenhove studies (2016a, 2016b). Consequently, the observed similarities between our findings and the activations identified in Gauthier and van Wassenhove study (2016b) for spatial distance computation may be attributed to the spatialization of time induced by our task, which emphasised the spatial representation of time. To support this hypothesis, we selectively masked our neural activity associated with the general MTT process and found that the temporo-parietal, retrosplenial, temporal medial and frontal areas resisted, suggesting that they are specifically involved in the perceived temporal distance computation.

In conclusion, our study provides insights into the mechanisms underlying the processing of subjectively perceived temporal distances in the MTT task, thereby enhancing the ecological validity of the task. The functional imaging findings show posterior parietal, temporal and frontal areas subtending the PTD effect, a network which appears very similar to the one engaged in spatial distances processing. The behavioural results also reproduce spatio-temporal effects related to the distance of events. Thus, our study supports the hypothesis of a common cognitive representation between space and time, as suggested by the ATOM theory (Walsh 2003; Bueti and Walsh 2009). According to an alternative yet interesting hypothesis, time and space (along with numbers) might interact with each other only at the functional level of working memory. This is suggested by the observation that all three dimensions - time, space, and numbers - require spatial attention and serial ordering within working memory to accomplish tasks (van Dijck et al., 2013). In the same vein, during the MTT task, working memory may build a spatial representation of time, by guiding attention towards long-term memory representations of space and time, thus facilitating the retrieval of past and the imagination of future events. Future research will be needed to disentangle the hypothesis of the spatial representation of time from the spatialization of temporal processes in the working memory.

Limitations

Our study provides an initial exploration of the role of perceived temporal distance in Mental Time Travel, although our experimental design prevents us from directly comparing the effects of objective and perceived temporal distances on MTT and their associated neural correlates. Future studies, specifically designed to directly contrast these two types of temporal distances, are necessary to enhance our understanding of their implications in MTT and of time perception.

General discussion

The representation of time is intertwined with spatial cognition in everyday life and language, and in the brain.

The perception of time relies on distinct cognitive functions and is supported by specific neural networks. In particular, episodic memory is required in recalling the Past, whereas episodic future thinking allows to imagine a possible Future scenario, and these cognitive functions are mediated by medial temporal regions and medial frontal areas respectively. Nonetheless, the brain characterizes, measures, and manipulates the temporal dimension of events, through spatial representations. Time is indeed represented through a spatial code, analogous to the one employed for encoding physical space. Furthermore, this spatial characterization of time is susceptible to spatial manipulations.

Many studies, both in healthy subjects and in clinical populations, supported this hypothesis.

The most supported representation of time is the Mental Time Line (MTL), i.e., a spatial axis oriented from left to right (at least in Western cultures), where the Past is located to the left and the Future to the right of the Present moment. The ability to remember the Past and envision the Future, projecting oneself to moments of the subjective time different from the Present, is called Mental Time Travel (MTT). This capacity requires an egocentric remapping of the temporal context and permits the sequential ordering of events on the MTL. In addition, several studies demonstrated that this ability can be manipulated through the modulation of spatial attention. Indeed, spatial attention is the medium for accessing the spatial representation of time. Therefore, the manipulation of the orientation of spatial attention affects the representation of time, too. Another factor supporting the representative association between time and space is the effect of Temporal Distance (TD), which refers to how far away events are from a certain temporal location. TD can modulate the ability to mentally travel in time and the underlying neural circuit.

The present thesis contributes to the existing scientific literature by investigating the neural bases of the modulation of the spatial attention and of the subjectively perceived temporal distance of events.

In the first experiment, the neural networks subtending the effects of the deviation of the spatial attention on the spatial representation of time and on the MTT ability were investigated. The MTT task was adapted to an fMRI protocol and conducted before and after a single session of prismatic adaptation (PA), which induced a leftward shift of spatial attention. As an effect of PA, we found improved performance selectively when participants projected to the Past and responded to relative past events, consistently with Anelli et al. (2016a; 2018a; 2018b). The behavioural experiment on the control group of subjects, exposed to neutral lenses, confirmed that the effects on MTT were not merely due to familiarisation or task repetition. At the functional level, we identified a fronto-parietal network mediating the PA effects on MTT, which comprises bilateral inferior parietal lobule (IPL), bilateral superior temporal gyrus (STG) and left inferior frontal gyrus (IFG). Therefore, starting from our results, we proposed an anatomo-functional model aimed at explaining the functioning of PA on the activity modulation during the MTT task. This model represents the first attempt to integrate anatomical, functional, and behavioural data on the effects of PA and MTT into a single framework. Specifically, we propose that PA first affects the parietal areas. Indeed, after the deviation of spatial attention, we found a reduction of activation in right IPL, which was related to the ability to project towards the Future, whereas the left IPL mediates the Past Self-Projection, coherently with Arzy et al. (2009a) and Gauthier and van Wassenhove (2016a). The activity of the left IPL correlated with the inhibition of the left SFG, which was involved when participants judged relative future events before PA, consistently with Ciaramelli et al. (2021a); Stendardi et al. (2021) and Guathier and van Wassenhove (2016a). Accordingly, the inhibition of this prefrontal area may facilitate the ability to judge relative past events. Finally, the modulated activity of the parietal areas correlated with the increased activity in bilateral STG after the PA procedure. STGs may support the effects of PA during the MTT task, in line with Luauté et al. (2009), Karnath et al. (2001) and Shah-Basak et al. (2018). According to our anatomo-functional model, we speculate that PA with a rightward shift may impact the IPLs, increasing the activation of the right one for Future projection. Indeed, Anelli et al. (2018) showed that patients with right brain damage and left neglect exhibited worse performance in responding to future events, because of a combination of spatial working memory deficits and of rightward attentional bias. Hence, inducing a rightward shift of spatial attention would modulate the balance between the parietal areas in orienting spatial attention towards the future. Then, the bilateral IPL would activate the STGs in order to maintain the PA effects, lastly enhancing the activity of the left SFG. This increment of activity in left SFG, in turn, may contribute to the improvement of responsiveness to relative future events, as expected after the rightward shift of spatial attention. Overall, we could speculate that the rightward shift of spatial attention induced by PA would result in an improvement in processing future events, mediated by increased activity of left SFG.

Further research will be needed to confirm our findings and to support our model. A direct comparison of the modulation of the neural activity as a consequence of either leftward or rightward shifts of spatial attention during the MTT task may clarify the role of each brain area involved in these processes. In particular, the analysis of the effective functional connectivity between the brain areas involved in mediating PA effects on MTT could validate our model. Furthermore, it would be useful to submit right and left brain-damaged patients to our fMRI protocol and to investigate in vivo how brain lesions can modulate the normal functioning of the MTT network, and how PA affects the neural plasticity in these patients. Finally, the consequences of PA during MTT could be investigated in amnesic patients, too. This could contribute to understanding whether the modulation of spatial attention can be generalized also to the memory level.

In the second experiment, the effects on MTT, and the underlying neural bases, of the perceived temporal distance (PTD) of events were investigated. The aim of this research question was to overcome the a-priori dichotomous categorization of events as either close or far that had been adopted in previous studies (Arzy et al. 2009b; Gauthier and van Wassenhove, 2016a). Furthermore, we wanted to provide evidence supporting the spatial representation of time as a function of this new effect, in order to enhance the ecological validity of the MTT task. Therefore, we studied the PTD as a continuous variable, and how it can shape the BOLD signal. At the behavioural level, we found a causal linear effect of PTD on RTs. In particular, a shorter PTD results in a longer RT in relative-past and relative-future events in the Past, as well as in relative-past events in the Present, and for both relative-past and relative-future events when collapsing the Self-Projection conditions. This means that the closer the perception of the events, the slower the reaction time. Since the distance effect in the numerical and temporal domains is considered as evidence of the continuous representation of magnitudes, our results demonstrate that the PTD of events is represented on the MTL as a continuous variable. Coherently, at the functional level, we found the PTD effect for both relative-past and relative-future events on the neural network mediating MTT. Again, we found that the closer the perception of the relative past and relative future events, the higher the involvement of a cerebral network comprising bilateral angular gyrus, temporal and parietal areas, which include the temporo-parietal junction (TPJ), retrosplenial cortex, middle and superior frontal gyri. Furthermore, we found that the closer the relative future events were perceived, the higher the engagement of left parahippocampal and lingual gyri and of right cerebellum. This is in line with our hypothesis of an additional involvement of processes, such as attention, visual imagery, and cognitive resources, in constructing possible future scenarios, as compared to remembering past events.

These results are even more interesting when we consider them in the light of the distinct networks for the representation of egocentric distances in time and space proposed by Gauthier and van Wassenhove (2016b). Indeed, the PTD-related brain activations we found are strikingly similar to the neural network specific for the spatial representation of proximity reported by Gauthier and van Wassenhove (2016b). Thus, we propose that in a spatialized temporal task, as the MTT task certainly is, the neural substrates mediating the PTD effect are shared between time and space representations. This further supports the notion that temporal metrics in the brain are related to, and based on, the spatial metrics.

Further research is needed to disentangle the effects of the perceived TD from those of the objective TD, in order to understand which one can better explain the modulation of brain activity during the MTT task. Moreover, investigating the PTD effect in patients with brain lesions with or without neglect could extend our knowledge about the subjective perception of time in these patients, and also offer an insight on possible rehabilitation mechanisms. Finally, further studies could be carried out to investigate the effects of spatial attention modulation on perceived temporal distances in pathological conditions in which PTD has been found to be altered, such as anxiety and depression (Rinaldi et al. 2016).

In conclusion, this thesis investigates the neural circuits underlying the mental time travel ability, especially focusing on the space-time interactions demonstrated by the effects of spatial attention modulation, and on the perception of the temporal distances of events.

The findings exposed in the present thesis contribute insights into the brain mechanisms subserving the elaboration of time, the improvement of neglect following prismatic adaptation, and the subjective perception of the temporal distance of events.

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Supplemental Materials

Experiment 1

<u>Materials and method: Stimuli</u>

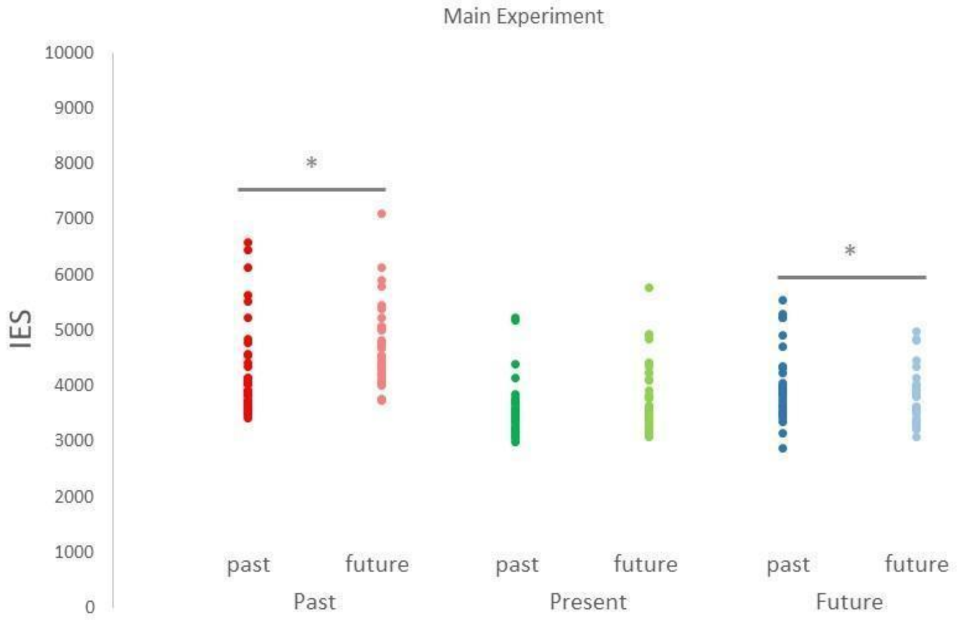
Supplementary Table 1

	PAST	PRESENT	FUTURE
past-personal	First best friend First school trip First time at the sea Bicycle without wheels 10th birthday First day of school	First time at the dentist 10th birthday First school day First political vote Maturity examination Driving license	Graduation 30th birthday Maturity examination First political vote First salary Driving license
future-personal	30th birthday First political vote First son Maturity examination Leave the hometown Driving license	30th birthday First son Silver wedding Son marriage Graduation First salary	Living on the moon Retirement Silver wedding Son marriage Son graduation 50th birthday
past - non personal	Princess Diana's death Freddy Mercury's death Fall of Berlin wall Chernobyl disaster September 11th Man on the moon	Obama's election Milan Expo Notre Dame fire Charlie Hebdo attack September 11th Gaddafi's death	Obama's election First use of Euro Gaddafi's death Pope Francesco's election Tokyo Olympics Napolitano's election
future - non personal	Notre Dame's fire Charlie Hebdo attack Milan Expo Tokyo Olympics Pope Francesco's election Woman president in USA	Peace in middle east Completely defeat illnesses Woman president in USA Completely defeat mafia End of the world Completely defeat world hunger	Flying car World peace Completely defeat mafia Completely defeat illnesses End of the world Completely defeat world hunger

List of events.

Behavioural Results: Pre PA session

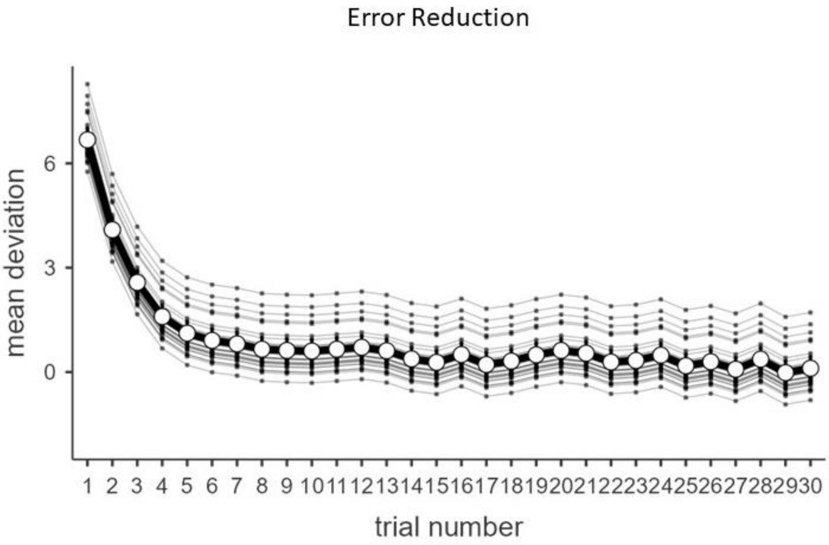
Supplementary Figure S1



Behavioural results of Pre-PA session. Self-Projection x Self-Reference interaction on IES in the Pre-PA session. Dark and light colours indicate past and future Self-Reference respectively. Asterisks indicate significant differences at p<0.05).

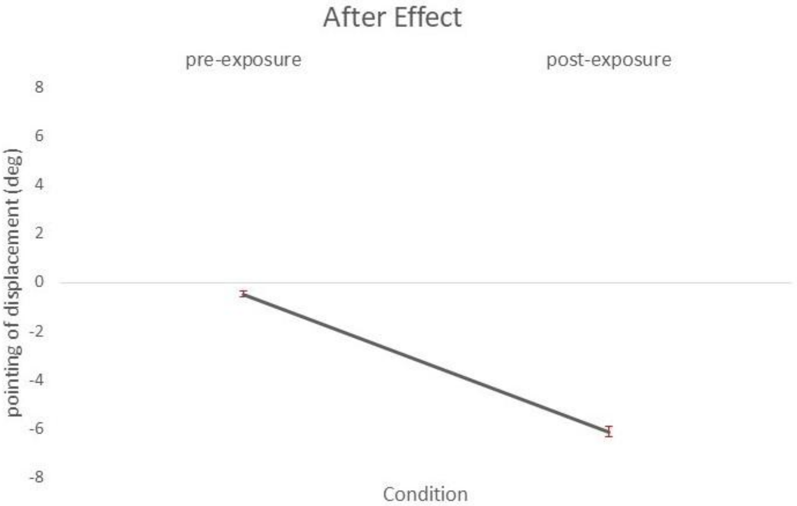
Prismatic Adaptation (PA)

Supplementary Figure S2



Prismatic adaptation results: Results showing the decrease of the mean deviation (i.e. the Error Reduction, ER) during the PA exposure. The ER means that participants successfully adapted to prismatic lenses.

Supplementary Figure S3



Results demonstrating after-effects of PA. The graph presents mean displacement of participants' invisible pointing before and after PA. Negative values indicate a leftward pointing displacement with respect to the target's actual location.

Functional results: Whole brain Pre-PA>Post-PA contrast

Supplementary Table S2

Anatomical region	BA	side	K	Z_E	Spatial coordinates (MNI)		
					x	y	z
Parahippocampal gyrus, Hippocampus, Amygdala		*r*	31	>8	24	-16	-22
				7.21	18	-10	-19
Superior and Middle Frontal gyrus, Anterior Cingulate, Supplementary Motor Area	8, 9, 10, 32, 6	*r/l*	1522	>8	-24	26	47
				>8	-6	53	32
				7.56	12	35	53
Caudate nucleus, Thalamus, Putamen, Lentiform Nucleus, Insula, Globus Pallidus		*r/l*	1212	>8	18	20	5
				>8	-12	20	5
				>8	-15	5	17
Angular gyrus, Postcentral gyrus, Inferior Parietal lobule, Inferior and Middle Temporal gyrus, Supramarginal gyrus, Precuneus, Middle Frontal gyrus	40, 39, 2, 3,4,7, 19, 5, 22, 37	*r*	919	>8	45	-58	32
				7.59	48	-61	17
				7.39	42	-25	50
Middle Temporal gyrus, Inferior Parietal lobule, Angular gyrus, Supramarginal gyrus, Superior Temporal gyrus, Superior Parietal lobule, Precuneus, Superior Occipital gyrus	39, 40, 22, 7, 19	*l*	573	>8	-42	-73	29
				>8	-42	-70	41
				7.17	-42	-61	20
Cerebellum, Precuneus, Fusiform gyrus, Parahippocampal gyrus, Middle & Inferior Occipital gyrus, Lingual gyrus, Posterior Cingulate, Inferior & Middle Temporal gyrus	7, 19, 36, 37,23,30, 31,18,20	*r/l*	2076	7.76	0	-58	-19
				7.66	18	-76	-34
				7.55	-27	-40	-16
Inferior Frontal gyrus		*r*	21	6.56	42	23	14
Precuneus, Cuneus	19, 7	*l*	38	6.49	-18	-85	38
				5.33	-24	-76	35
Middle Frontal gyrus	46	*r*	27	6.45	42	56	-4
				5.47	39	44	-13
Inferior Frontal gyrus	45	*l*	26	6.28	-57	20	11
Inferior Frontal gyrus	47	*r*	53	6.22	54	35	-7
Middle Occipital gyrus	18, 19	*l*	20	6.14	-27	-94	8
				5.63	-18	-91	17
Middle Frontal gyrus	10	*l*	54	6.05	-39	50	11
				5.89	-33	50	2
Hippocampus, Thalamus		*l*	43	6.04	-30	-22	-7
				5.49	-24	-31	5
Inferior Frontal gyrus	47	*l*	23	5.97	-48	35	-10
				5.07	-42	23	-10
Superior and Middle Frontal gyrus	10, 46	*r*	55	5.93	27	65	8
				5.83	15	62	14
				5.71	24	65	20
Middle Frontal gyrus	46	*r*	30	5.81	51	38	23
Middle Frontal gyrus	46	*r*	27	5.56	48	20	35
				5.23	45	17	44
Inferior Frontal gyrus	46	*l*	12	5.49	-51	17	-4
Inferior Frontal gyrus	46	*l*	17	5.42	-51	38	11
Precuneus		*l*	13	5.31	-9	-49	56
				4.75	-6	-40	50
Middle Occipital gyrus	18, 19	*r*	23	5.13	33	-79	2
				4.86	30	-82	14

Areas of increased signal for the Pre-PA>Post-PA contrast (p<0.05 FWE corrected, k≥0), displaying clusters >10.

ROI analyses Pre- compared to Post-PA session:

When considering the Pre- vs Post-PA contrast, the ROI analyses of the right and left STG showed a significant effect of Session ($F_{1,36}$= 14.79, p<0.001, η^2_p= 0.29; $F_{1,36}$=12.62, p<0.01, η^2_p=0.26) with an increase of activation in Post-PA, as compared to Pre-PA.

A main effect of Session was also found left SFG ($F_{1,36}$=19.45, p<0.001, η^2_p=0.35) with a decreased activity in Post-PA, as compared to Pre-PA (Fig. 5 in main text).

Functional results: PPI Analyses

Supplementary Table S3

Anatomical region	**BA**	**side**	**K**	**Z_E**	**Spatial coordinates (MNI)**		
					x	**y**	**z**
Superior and Middle Temporal gyrus, Anterior Insula	41, 42, 22, 21	*l* *r*	474 553	6.07 5.84	-57 63	-22 -10	5 5
Middle, Inferior & Superior Occipital gyrus, Lingual gyrus, Cuneus, Fusiform gyrus	18, 19, 17	*r* *l*	342 391	5.26 5.01	24 -36	-94 -82	-4 -10
Supplementary Motor Area, Cingulate gyrus, Middle Frontal gyrus	6, 32, 24	*r/l*	323	4.77	0	2	62
Precuneus, Superior & Middle Occipital gyrus, Inferior & Superior Parietal lobule, Angular gyrus	7, 40	*l* *r*	135 262	4.69 4.68	-27 27	-55 -64	44 44
Anterior Insula, Inferior Frontal gyrus	47, 45	*r*	65	4.55	36	20	2

Results of PPI analysis of right IPL: Areas of reduced connectivity with right IPL ROI; 3dClustSim correction for multiple comparisons, α < 0.05: voxel-wise intensity threshold of p < 0.001, k > 62voxels).

Functional results: PPI Analyses

Supplementary Table S4

Anatomical region	**BA**	**side**	**K**	**Z_E**	**Spatial coordinates (MNI)**		
					x	**y**	**z**
Medial Superior Frontal gyrus	10, 9	*l*	83	4.34	-3	56	20

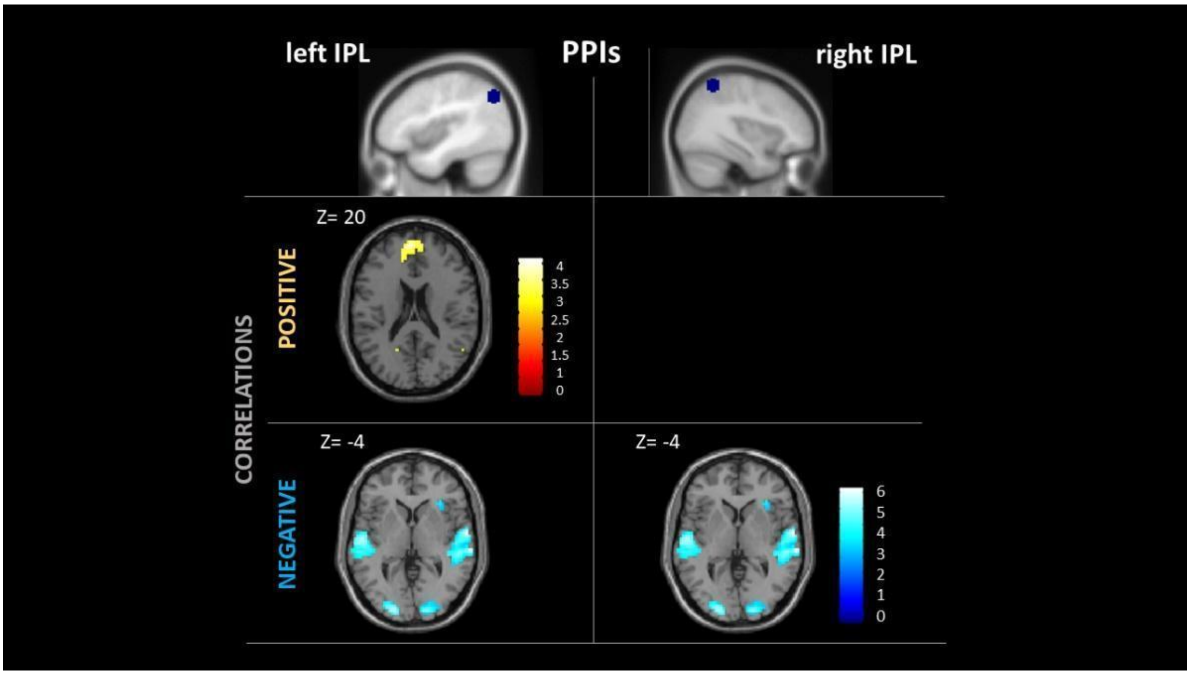
Results of PPI analysis of left IPL: Areas of increased connectivity with the left IPL ROI; 3dClustSim correction for multiple comparisons, $\alpha < 0.05$: voxel-wise intensity threshold of $p < 0.001$, $k > 74$ voxels).

Supplementary Table S5

Anatomical region	**BA**	**side**	**K**	**Z_E**	**Spatial coordinates (MNI)**		
					x	**y**	**z**
Inferior and Middle Occipital gyrus, Lingual gyrus, Fusiform gyrus	18, 17, 19	*l*	384	5.60	-36	-85	-10
Superior and Middle Temporal gyri, Anterior Insula	22, 21, 41, 42	*r*	531	5.50	63	-7	5
		l	629	5.45	-57	-40	8
Middle and Inferior Occipital gyrus, Lingual gyrus	18, 17, 19	*r*	242	5.19	21	-94	-4
Inferior and Middle Frontal gyri, Precentral gyrus	46, 9, 45	*r*	80	4.73	45	23	26
		l	161	4.52	-42	23	23
Inferior and Superior Parietal lobule, Precuneus, Angular gyrus	7, 19, 40	*r*	74	4.51	27	-64	38
Supplementary Motor Area	6, 8	*l*	115	4.42	-3	2	59
Superior Parietal lobule	40	*l*	87	4.16	-27	-58	44

Results of PPI analysis of left IPL: Areas of decreased connectivity with left IPL ROI; 3dClustSim correction for multiple comparisons, $\alpha < 0.05$: voxel-wise intensity threshold of $p < 0.001$, $k > 74$ voxels).

Supplementary Figure S3

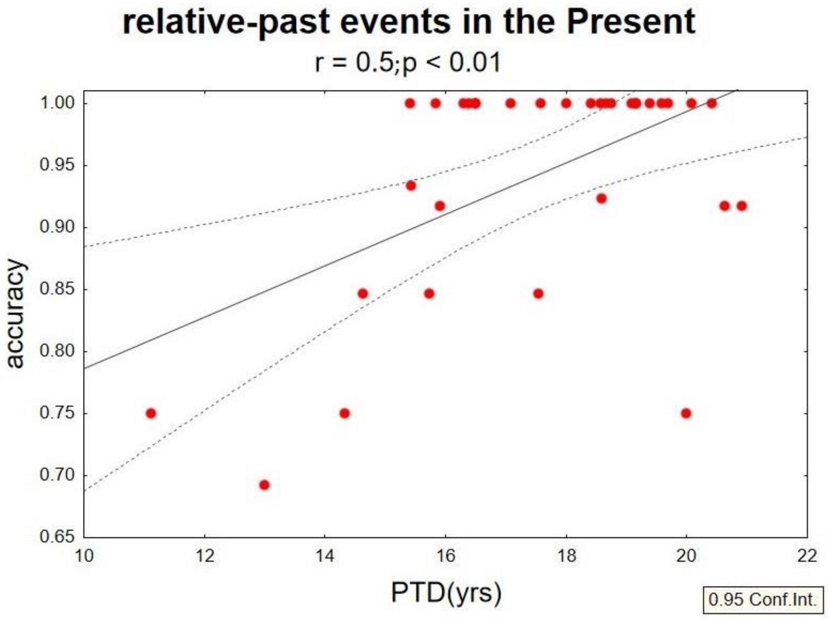


PPI analyses results: Results of the PPI analyses between neural activity in the left and right IPL and the psychological variable of interest (past events in Past projection). In yellow: positive correlation between neural activity within the left IPL and the psychological variable of interest (3dClustSim correction for multiple comparisons, α < 0.05: voxel-wise intensity threshold of p < 0.001, k > 74 voxels); in blue: inclusive mask of negative PPI between neural activity within bilateral IPL and the psychological variable of interest (3dClustSim correction for multiple comparisons, α < 0.05: voxel-wise intensity threshold of p < 0.001, k > 62 voxels). Clusters are superimposed on the SPM single subject template.

Experiment 2

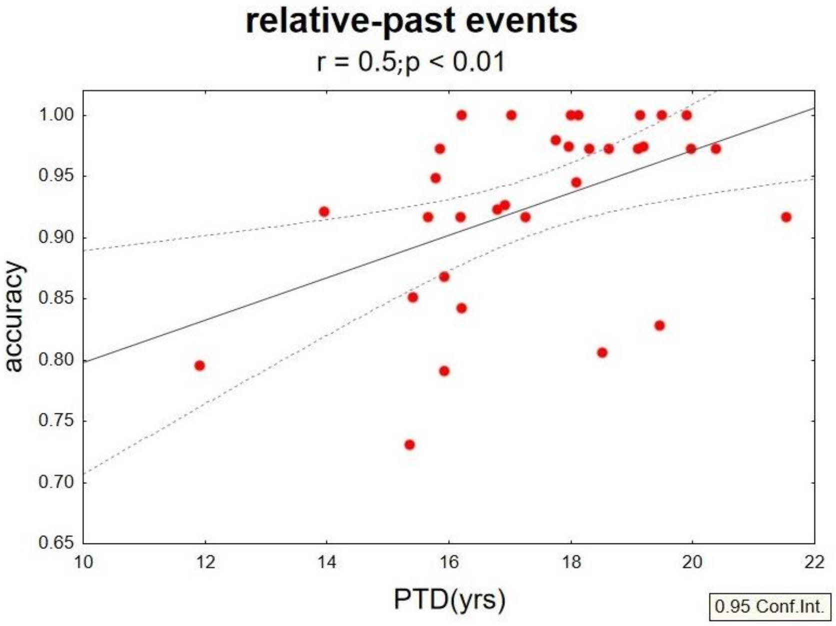
Behavioural results: Accuracy

Supplementary Figure S1



Behavioural results. Mean accuracy (percentage of correct answers) as a function of mean PTD for relative-past events (absolute value) in the Present self-projection condition.

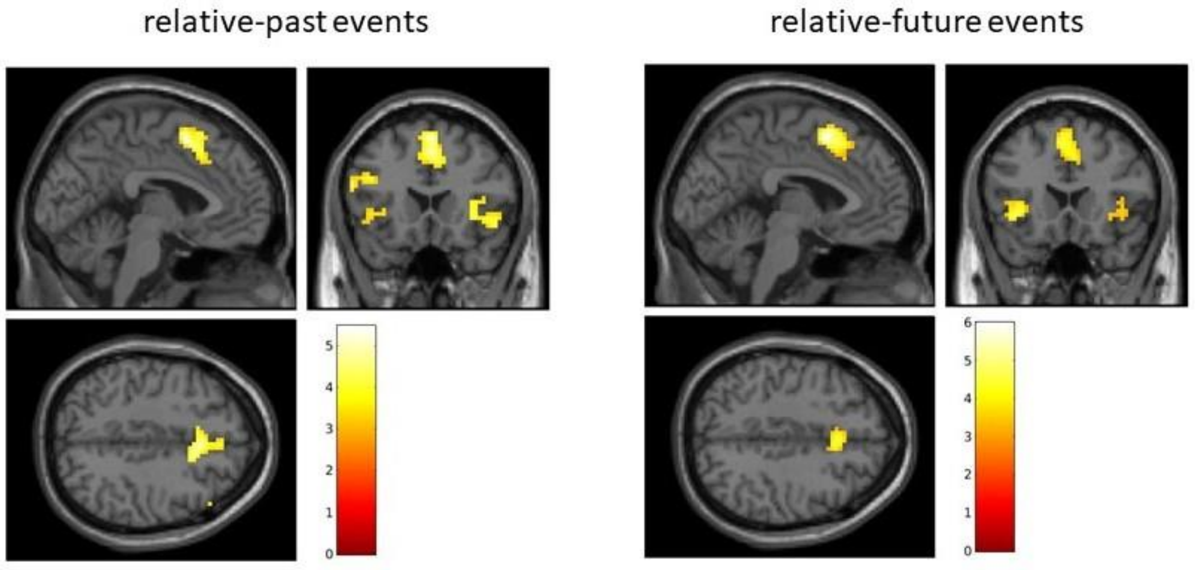
Supplementary Figure S2



Behavioural results. Mean accuracy (percentage of correct answers) as a function of mean PTD for overall relative-past events (absolute value; Self-Reference condition).

Functional results: parametric analyses conducted on RTs

Supplementary Figure S3



Brain regions whose activity exhibits linear relationships with RTs as a function of Self-Reference conditions. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of α < 0.05 (p < 0.001 and k > 69 voxels). Images are in neurological convention (right is right). Color bars represent T-values.

Supplementary Table S2

Results of the linear relationship with RT for relative-past events

Anatomical regions	**BA**	**Side**	**K**	**T**	**MNI coordinates**		
					x	**y**	**z**
Supplementary Motor Area, Superior Frontal gyrus, Cingulate gyrus	6, 8	*l*	323	5.45	0	11	53
Insula, Inferior Frontal gyrus	45, 47	*r*	104	4.90	33	26	-1
Insula, Inferior Frontal gyrus	45, 47	*l*	88	4.75	-30	26	-1
Inferior Frontal gyrus	9	*r*	81	4.46	39	53	23
Inferior Frontal gyrus	9, 10	*l*	142	4.32	-48	14	26

Areas of significant changes in fMRI signal as a function of RT for relative-past events; BA = Brodmann area; L = left; R = right. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of α < 0.05 (p < 0.001, k > 69 voxels)

Supplementary Table 3

Results of the linear relationship with RT for relative-future events

Anatomical regions	**BA**	**Side**	**K**	**T**	**MNI coordinates**		
					x	**y**	**z**
Supplementary Motor Area, Superior Frontal gyrus, Cingulate gyrus	6, 8	*l*	242	5.97	-3	8	53
Insula, Inferior Frontal gyrus	45, 47	*r*	76	4.93	33	26	2
Insula, Inferior Frontal gyrus	45, 47	*l*	100	4.84	-39	17	-4

Areas of significant changes in fMRI signal as a function of RT for relative-future events; BA = Brodmann area; L = left; R = right. A double statistical threshold was applied to obtain a combined significance, corrected for multiple comparisons, of α < 0.05 (p < 0.001, k > 69 voxels)

Behavioural data analyses and results at MTT task

Two Separate Repeated-measures ANOVAs were conducted on reaction times (RTs) and accuracy, having Self-Projection (Past, Present, Future) and Self-Reference (relative-past, relative-future) as within-participants factors. Effect size was reported as partial eta squared (η^2_p). When significant, interactions were followed-up by Duncan Post-hoc tests. Mean values and standard error means (SEM) were reported for each condition.

Reaction Time

Data showed a significant main effect of Self-Projection ($F_{2,64}$= 76.91; p< 0.0001; η^2_p= 0.71) with all the conditions different from each other (mean RT in Past 3866.87 ± 64.1; Present 3365.28 ± 47.4; Future 3625.9 ± 52.2). There was also a significant Self-Projection x Self-Reference interaction ($F_{2,64}$= 6.65; p< 0.01; η^2_p= 0.17). Post-hoc analysis showed that performances for relative-future events were significantly faster as compared to relative-past events when participants were projected to the Future (mean 3526.24 ± 50.21 vs 3725.72 ± 68.29 ms; p < 0.01).

Accuracy

Data showed a significant main effect of Self-Projection ($F_{2,64}$= 10.63; $p < 0.0001$; η^2_p= 0.25), with significantly lower accuracy in Past Self-Projection (0.88 ± 0.0) as compared to both the other conditions (1; Present 0.92 ± 0.01; Future 0.93 ± 0.01), which did not different from each other. The Self-Reference main effect was also significant ($F_{1,32}$= 8.81; $p < 0.01$; η^2_p= 0.21), with lower accuracy for relative-future as respect to relative-past events (mean 0.89 ± 0.01 vs 0.93 ± 0.01).

Functional data analyses and results of the MTT task

Functional data were pre-processed and analysed using MatLab (MathWorks Inc., Natick, MA, USA) and SPM12 softwares (Wellcome Department of Imaging Neuroscience). The following pre-processing steps were used: slice-timing, spatial realignment, normalization to the MNI template and smoothing with a 6 mm full width Gaussian filter. Single-subject statistical analysis was performed using the General Linear Model (GLM), where the time-series data were modelled as a series of events convolved with a canonical hemodynamic response function. Regressors of interest were as many as the combinations of factors, i.e., the experimental conditions. Motor answer, errors and head-motion parameters (translations and rotations) were entered as nuisance variables. Each experimental condition was compared to the baseline and the other conditions and individual contrast images were used for the whole brain random effect analysis. A full-factorial ANOVA with Self-Projection (Past, Present, Future) and Self-Reference (past, future) as factors was conducted on single subject contrast images.

During the MTT task execution a widespread network was activated, comprising right Parahippocampal gyrus and Postcentral Gyrus (BA 1, 2, 3, 30, 36), and bilateral Posterior Parietal Cortex (BA 39, 40), Precuneus (BA 19), Occipital cortex (BA 18, 19), Cerebellum, Basal Ganglia and Inferior, Middle and Superior Frontal gyri (BA 10, 45, 46, 47). For more detailed results, Casadio et al. (2023).

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