



Envisioning the future: An ALE meta-analysis on neural correlates of future thinking, prospective memory and delay discounting

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ARTICLE INFO

Keywords:

Prospection
Future-oriented cognition
Prospective memory
Future thinking
Delay discounting
Activation likelihood estimation
Default Network
Saliency Network
Prediction
Predictive brain

ABSTRACT

Our representations of the future are processed in the service of several different cognitive functions, including episodic future thinking, prospective memory, and temporal discounting. The present meta-analysis used the Activation Likelihood Estimation method to understand whether there is a core network underlying future-oriented cognition and to identify the specific brain regions that support future-related processes in each function. Following the PRISMA guidelines, a total of 24, 19, and 27 neuroimaging studies were included for future thinking, prospective memory, and temporal discounting, respectively. Results showed that there is no specific region or network for the future. Instead, the 'future' seems to be represented on an anterior-posterior tangibility gradient, based on the level of abstractness/concreteness of the simulated scenario. Additionally, future-oriented cognition is mediated by two distinct networks: the Default Network and the Saliency Network. The Default Network is mainly active in supporting future thinking, whereas the Saliency Network is primarily involved in prospective memory and delay discounting.

1. Introduction

"More than anything, I remember the future."

Salvador Dalí

Over the course of each day, human beings devote considerable time to anticipating, making plans for, and contemplating the future. All these activities fall under the umbrella term of *prospection*, or future-oriented cognition, which refers to the mental processes involved in representing future events, outcomes, and consequences (Gilbert and Wilson, 2007). Future-oriented cognition encompasses multiple functions, including making plans, envisioning future scenarios, and considering how one's current actions might affect future outcomes. It can be directed toward ordinary events, such as remembering to go to the grocery store after work, as well as more significant life choices that greatly impact our success and happiness, such as deciding to accept a job or get married. Although there are countless ways in which people consider the future, a taxonomy of future-oriented cognition developed

by Szpunar and collaborators (2014) suggests that it can be grouped into four modes: simulation (creating a detailed mental image of the future), prediction (estimating the likelihood of a given event and possible reactions to it), intention (encoding a future goal), and planning (organizing the steps necessary to achieve a goal). Importantly for our aims, the framework by Szpunar and collaborators (2014) related these modes of future-oriented cognition to two distinct types of representations that are episodic and semantic, which differ for the level of abstractness/concreteness. The term 'episodic' is indeed meant to refer to representations in relation to more concrete and specific autobiographical events that may arise in the future (e.g., remembering to pick up bread at the grocery store). The term 'semantic' is meant to refer to representations (i.e., simulations, predictions, intentions, and plans) that are more abstract or general states of the world that may be placed in the future (e.g., thinking about how to have a more meaningful life).

Also, *prospection* can be studied through three types of future-related activities: 1) episodic Future Thinking (FT), which involves the ability to imagine and anticipate one's personal future events (Atance and O'Neill, 2001; Schacter et al., 2008; Szpunar, 2010); 2) Prospective

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Memory (PM), which enables the encoding of an intention and remembering to accomplish it at the correct time in the future (Brandimonte, 1996); and 3) intertemporal decision-making, typically studied using the Delay Discounting (DD) task, which evaluates the process of choosing between alternatives that have consequences occurring at different points in time (Bickel and Marsch, 2001).

In classical episodic FT tasks (e.g., Addis et al., 2007), participants are presented with word cues and instructed to imagine specific personal events from future time periods in response to these cues. In PM tasks, participants are asked to encode and remember to perform an intention (e.g., pressing a specific computer key) at a specific time (e.g., every 2 min) or when a specific PM cue (e.g., a particular word) occurs in the future, while simultaneously executing an ongoing task such as a lexical decision task or a category decision task (Einstein and McDaniel, 2005). In DD tasks, participants are asked to choose virtually between small but immediate amounts of money or larger but delayed amounts of money, such as "Would you prefer €10 right now or €20 in a week?" (Duckworth and Seligman, 2005; van den Bos and McClure, 2013). These future-related tasks have largely been examined in isolation from each other, despite the existence of close relationships between them. Although they have different purposes and involve distinct cognitive mechanisms, all of these tasks encompass a collection of processes that are intrinsically related to the encoding and manipulation of representations of future scenarios. These scenarios can involve events, intentions, or rewards. The main similarity among the three future-related functions is indeed the process of forming and maintaining active representations of stimuli or events linked to a specific time in the future, without immediate action. However, they also differ in several aspects. Beyond the idiosyncrasies and specificities of their respective paradigms, three relevant differences are noteworthy. The first difference lies in the recruitment of external, stimulus-dependent processes versus internal, stimulus-independent processes. While representations of the future in PM and DD are strictly anchored to external cues (monitoring for the presence of the PM cue and evaluating the amount of reward, respectively), the future scenarios generated in FT tasks are initially elicited by the cue but are then extensively manipulated and transformed independently. Hence, FT appears to rely more on internal processes than the other two paradigms. Secondly, the level of abstractness and complexity differs in the representations generated by the three types of paradigms used in neuroscience studies. In FT tasks, representations of future events are generally more abstract and complex (e.g., simulating a holiday next summer). On the other hand, PM and DD tasks require the formulation of more concrete and simpler representations. For instance, PM tasks involve representing a specific finger action in relation to a time/event cue, while DD tasks require representing a specific amount of money. The third point highlights the distinction in temporal scales of future processing across the paradigms. Specifically, FT and DD tasks elicit representations of the future that can span from days to years, while PM paradigms engage representations of future intentions within a few minutes.

Based on such similarities and differences, the main purpose of the present study is to evaluate the extent to which episodic FT, PM and DD enroll the same or different brain regions and networks, and to discuss what role specific brain regions would play in each future-oriented function. To do so, we conducted a quantitative meta-analysis of functional neuroimaging studies on prospection, and, through a conjunction analysis, we assessed whether there are areas commonly activated among the three functions. Also, we conducted discriminability meta-analyses to isolate brain regions that are more specifically activated in each one of the functions.

1.1. Future thinking

Humans have the capacity to vividly imagine the future, anticipating and simulating what might happen in their lives (Schacter et al., 2015; Suddendorf and Corballis, 2007; Tulving, 2005). This ability, known as

episodic Future Thinking (FT), is considered a unique function of human cognition and plays a crucial role in shaping individual behavior. It helps individuals anticipate the future consequences of their actions and adjust their behavior accordingly (Suddendorf and Corballis, 2007).

A review of several diary and everyday experience studies conducted by Kvavilashvili and Rummel (2020) revealed that individuals often think about their future in the form of spontaneous thoughts that arise when their minds wander, rather than being entirely focused on a task. Furthermore, future-related thoughts occur more frequently than thoughts about the past. According to some studies (e.g., Gardner and Ascoli, 2015), these future-related thoughts frequently 'pop up' in everyday life, occurring once every 2–4 min.

A substantial body of evidence shows that imagining the future shares neurocognitive mechanisms with remembering the past (for review, see Schacter et al., 2007, 2012). The first evidence was reported by Tulving (1985), who described the case of an amnesic patient unable to remember any events from their life or mentally project themselves into the future. Based on Tulving's earlier observations, the constructive episodic simulation hypothesis was developed (Schacter and Addis, 2007b, 2007a, 2020). This hypothesis suggests that episodic memory plays a crucial role in simulating the future. According to this view, we construct possible future scenarios by recombining elements of our memories.

The constructive episodic simulation hypothesis has received substantial support from neuroimaging data, which consistently show that the brain regions activated during the retrieval of autobiographical memories closely overlap with those involved in the anticipation and simulation of future experiences (e.g., Addis et al., 2007; Botzung et al., 2008; Hassabis and Maguire, 2007; Szpunar et al., 2007). This network of commonly activated regions includes the medial prefrontal cortex (mPFC), the medial temporal lobes (MTL), the posterior cingulate cortex (PCC), with particular emphasis on the retrosplenial cortex, and lateral parietal and temporal regions (Hassabis and Maguire, 2007; Schacter et al., 2007, 2012). This pattern of brain regions constitutes a core network that underlies both the recollection of past events and the construction of future events (Schacter et al., 2007; Stawarczyk and D'Argembeau, 2015) (see Spreng et al., 2009 for a meta-analysis).

This core network overlaps the set of brain regions labelled as "the Default Network" (Buckner and Carroll, 2007; Schacter et al., 2012). The Default Network includes regions that are typically activated during rest periods (Buckner et al., 2008; Raichle et al., 2001; Shulman et al., 1997) and are engaged in internally-directed cognition and self-generated activities (Andrews-Hanna et al., 2014), such as mind-wandering, navigation, theory of mind, creativity activities, memory, counterfactual thinking and self-referential processing (van Genugten and Schacter, 2021). As such, the Default Network seems to be remarkably engaged when thinking about the future, which is an intrinsically self-generated and internally directed activity.

1.2. Prospective memory

Prospective memory (PM) refers to remembering to carry out a planned action in the future (Brandimonte, 1996; Kliegel et al., 2008), such as reminding oneself to feed the cat before going to work or taking the birth control pill every day at the same time. Given the significant amount of time spent forming and fulfilling intentions, it is estimated that roughly 50% of daily forgetting is caused by failures in PM (Crovitz and Daniel, 1984).

PM comprises separate phases, including intention encoding, intention maintenance, intention retrieval and execution (Kliegel et al., 2002; Marsh et al., 2002), each one relying upon specific neurocognitive processes. Furthermore, fulfilling PM intention can be mediated by various processes, which can be clustered under the 'strategic monitoring' and 'spontaneous retrieval' labels (Einstein and McDaniel, 2005). Strategic monitoring involves a set of top-down attentional and memory processes necessary for detecting the presence of the PM cue in

the environment and for maintaining the intention active and refreshed in mind (Cona et al., 2020). Spontaneous retrieval is instead a bottom-up process and refers to the automatic capture of attention by the PM cue and the activation of related intention from memory (Einstein and McDaniel, 2005).

PM tasks also differ in the ways in which intentions can be cued (McDaniel and Einstein, 2007). Three types of PM tasks are classified: event-based PM (remembering to do something when a particular event/stimulus occurs), time-based PM (remembering to do something at a particular time or after a period) and activity-based PM (remembering to do something before, during or after a particular activity).

The multifaceted nature of PM tasks is translated in the widespread amount of distinct brain regions differently activated depending on the features of the PM task. Several studies focused on the role of the anterior prefrontal cortex (aPFC, Brodmann's area 10), which plays a crucial role in maintaining and retrieving the intention (e.g., Burgess et al., 2001, 2003; den Ouden et al., 2005; Gilbert et al., 2009; Momennejad and Haynes, 2012; Okuda et al., 1998; see Burgess et al., 2011 for a review). As compared with "uncontaminated" ongoing task blocks (in which the ongoing task was performed without any PM instruction), PM conditions are characterized by enhanced activity of lateral aPFC and decreased activity of medial aPFC. This pattern of activation/deactivation is explained within the Gateway hypothesis, lateral and medial aPFC regions comprise a mechanism that allow to balance the attention between the external ongoing stimuli and the internally represented intention (see (Burgess et al., 2007; Gilbert et al., 2005; Gilbert, Simons et al., 2006; Gilbert, Spengler et al., 2006).

A meta-analysis identified the brain activations associated with each of the PM phases, and discussed their functional role within the Attention to Delayed Intention (AtoDI) model (Cona et al., 2015). The encoding phase is associated with activations especially in the left hemisphere, including left lateral aPFC (BA 10), left inferior parietal lobule (BA 40) and postcentral gyrus (BA 2), and PCC regions (BA 23). Occipital regions and subcortical regions (i.e., caudate, thalamus) are also activated. In the encoding phase, indeed, the to-be-encoded PM stimulus would elicit a bottom-up capture of attention, mediated by the activity in ventral parietal regions, which are responsible for the direction of attention not only externally - towards the PM cues - but also internally, towards the to-be-encoded future intention (Ciaramelli et al., 2010; Corbetta and Shulman, 2002). The formation of the intention would be also related to PCC and left PFC activation (Gilbert et al., 2007). Finally, somatosensory regions would encode the set of actions for later execution.

In the maintenance phase, a consistent activation of the aPFC and regions of the dorsal fronto-parietal network, as pre-supplementary area (pre-SMA, BA 6), dorsolateral prefrontal cortex (BA 9), superior parietal lobule and precuneus (BA 7,19) was found. Parietal regions are responsible for the top-down allocation of attention towards the external PM cues and to the content of future intentions, represented by frontal regions (Cona et al., 2015).

In the retrieval/execution phase, a constellation of many different areas is involved. When the PM cue occurs in the environment, the presence of such salient cue would be detected by the Salience Network (insula and anterior cingulate cortex). The PCC, together with ventral frontoparietal regions, would contribute to the bottom-up attention captured externally by the PM stimulus, and shifted internally, towards the internal representation of the future intention. Finally, the SMA areas, together with the somatosensory regions would implement the corresponding action (Cona et al., 2015).

1.3. Delay discounting

There are numerous decisions faced by humans that involve selecting between actions with outcomes accomplished at different times in the future. Interestingly, it is quite common for more desirable outcomes to require a greater investment of time and/or effort. Therefore, behaving

efficiently in many contexts requires the ability to delay gratification, foregoing immediate temptations. Since the extraordinary relevance and ubiquity of delaying gratification in a wide variety of life contexts such as health, academic achievement, and retirement savings (e.g., Bickel and Marsch, 2001), there has been a great interest in investigating how humans (as well as other animals) make such decisions.

The typical paradigm to describe this phenomenon in human participants is the DD task (Duckworth and Seligman, 2005; van den Bos and McClure, 2013) since the preference for smaller but sooner rewards over larger but later rewards is labeled as Delay Discounting (DD; Ainslie, 1975). Individual differences in delay discounting (DD) predict or correlate with a constellation of behavioral and real-life traits (see Cona et al., 2019, for a general overview). A stable preference for immediate smaller rewards is associated with various behaviors and life aspects, including substance addiction, antisocial and rule-breaking behaviors, withdrawal behaviors (Fossati et al., 2004), impulsive behavior (Lane et al., 2003), higher levels of stress and a high body mass index (Chen et al., 2017), higher levels of anxiety (Rounds et al., 2007), lower levels of self-efficacy, and reduced life satisfaction (Bickel et al., 2011).

However, the neurobiology underlying DD has not been completely understood. Based on the initial fMRI studies of DD, several dual-system models (e.g., the β - δ model) of decision-making have been developed (Bechara, 2005; Bickel et al., 2007). According to these models, decision-making processes depend on a balance of activation between two neurobiological systems (Bickel et al., 2007). The 'impulsive emotional system,' an evolutionarily older system that includes limbic and paralimbic regions (such as the amygdala, striatum, ventral pallidum, and nucleus accumbens), is activated when encoding immediate rewards. The control or 'patient rational' system (' δ '), which comprises more recently evolved regions in the prefrontal cortex (PFC) and anterior cingulate cortex (ACC), plays a crucial role in regulating the impulsive system and values both immediate and delayed rewards (Schüller et al., 2019). The ability to delay a reward in favor of a larger one has been found to be associated with stronger functional coupling between these two systems, specifically between frontal and control-related regions and subcortical regions (such as the amygdala and caudate) (Cona et al., 2019).

More recently, several meta-analyses of neuroimaging studies tried to identify the neural activations associated with each of the aspect involved in the multifaceted phenomenon of DD (Cui et al., 2022; Schüller et al., 2019; Smith et al., 2018; Wesley and Bickel, 2014).

For the aims of the present study, we focus on the regions involved in valuing and thus representing delayed future rewards. Delayed and immediate rewards were indeed linked to distinct patterns of neural activity during DD tasks. Processing of future rewards mainly involved the activation in the left dorsal insula, left inferior frontal gyrus (IFG), and left middle cingulate gyrus (Cui et al., 2022; Schüller et al., 2019; Smith et al., 2018). The cluster of left IFG and left insula was suggested to be responsible for the integration of temporal information about the two time points (e.g., present and foreseeable future) and to reconcile the contradictory relationships between time and reward (Cui et al., 2022; Wesley and Bickel, 2014).

1.4. The present study

The taxonomy of prospection (Szpunar et al., 2014) identified multiple future-oriented functions: Future Thinking, Prospective Memory, and Delay Discounting. These functions all involve processing and integrating information related to the future but differ in several aspects, such as the level of episodic and concrete representations versus semantic and abstract representations. This study was aimed to investigate the brain activations related to prospection (first aim) and to identify possible similarities and differences in neural activation among these three domains (second aim). More specifically, we asked whether a common "brain network of the future" exists.

Therefore, we performed an Activation Likelihood Estimation (ALE)

meta-analysis on neuroimaging studies of future-oriented processes, selecting, for each of the domain, the contrast that mostly emphasized the representation of future elements (which could be future scenarios/situations, actions, or rewards).

If there is a common brain network involved in dealing with future representations regardless of the type of task, FT, PM and DD should result in similar brain activation. By contrast, if encoding future representation is specific for the activity/function accomplished, it should be associated with different activation patterns for the three domains.

2. Methods

2.1. Literature search and studies selection

Articles included in the present meta-analysis were identified by a systematic literature search in PubMed and Google scholar databases, to retrieve relevant studies published before January 2023. For each domain, specific terms were utilized: for FT studies, the terms “future thinking”, “future simulation”, “mental time travel”, “future-oriented cognition” or “future orientation”; for PM studies, the terms “prospective memory”, “future memory”, “future intention” or “delayed intention”; for DD domain, the terms “delay discounting”, “temporal discounting” or “inter-temporal choice”. These keywords were combined (“AND”) with the terms “fMRI” or “PET” (and their expanded forms) to identify relevant functional neuroimaging studies. All studies reporting electrophysiological techniques (e.g., electroencephalography, magnetoencephalography, skin conductance response), transcranial magnetic stimulation (TMS), diffusion tensor imaging (DTI) and only behavioral methods were excluded.

Further studies were found by tracing the references from review articles (Benoit and Schacter, 2015; Cona et al., 2015; Seaman et al., 2022) and from the identified papers.

Three datasets (one for each domain) were created with the following features for each experiment: number of subjects, task, performed contrast, number of foci, coordinates system and coordinates localization.

The following inclusion criteria were used to select articles for the present meta-analysis:

- Only studies testing healthy young adults with no sign of neurological or psychiatric illness were considered. Articles including pathological populations were eventually selected only if reporting separately results from the control group. Studies reporting data only from older adults, children and adolescents were excluded, to avoid effects due to age.

- Only articles reporting whole brain analysis were included. Articles performing exclusively ROI analysis were excluded.

- Only articles performing functional activity analysis were included. Studies performing other types of analysis such as machine learning, functional connectivity or multivoxel pattern analysis were excluded.

- Only articles yielding a clear contrast that represented locations of greater activation for task-related conditions as compared with control or baseline conditions were included.

- Only articles reporting areas of peak activation in a standardized coordinate space (e.g., Talairach or MNI) were considered. Coordinates originally published in Talairach space were converted to MNI space using a linear transformation (Laird et al., 2010; Lancaster et al., 2007).

- Only articles reporting novel data from a sample size of at least 5 participants were included. Single case studies were excluded.

Moreover, for each selected study we included only the contrast that most strongly reflected the future component of the critical cognitive process in order to reduce heterogeneity among the sample of experiments (Müller et al., 2018). Contrasts focused on other phases or aspects unrelated to the process of future imagination were not included in our analysis.

For the Future Thinking (FT) paradigms, we selected contrasts that emphasized the representation of future events compared to past or

present events, as well as those favoring the simulation of new and congruent episodic future scenarios. Regarding the Prospective Memory (PM) tasks, we extracted foci of activation related to the encoding phase, where participants were shown cues and asked to form future intentions related to them. We also included contrasts between PM blocks (PM + Ongoing task block) and Control blocks (Ongoing task block), focusing on the maintenance of future intentions by removing the ongoing task components. These PM phases involve forming and actively maintaining information related to delayed intentions in the future.

For the Delay Discounting (DD) paradigms, we selected contrasts in which delayed choices were preferred over immediate ones. When participants chose delayed rewards, they were directing their attention and thoughts toward future scenarios. In contrast, when choosing immediate rewards, participants may not have projected themselves into future scenarios. In articles that did not explicitly investigate this distinction, we selected coordinates referring to activated regions during the DD task or those correlating with the temporal factor by which the utility is discounted. Additional details about the selected contrasts can be found in Table 1. Based on these criteria, a total of 24, 19 and 27 original articles were found eligible to be included in the present meta-analysis, respectively for FT, PM and DD studies. A list of all the studies and contrasts included is shown in Table 1.

Literature screening and final selection have been performed according to the latest version of the PRISMA guidelines (Page et al., 2021). The procedure is summarized in the PRISMA flow diagrams (see the Supplementary Materials).

2.2. ALE consistency analysis

For a quantitative assessment of convergence across experiments, the Activation Likelihood estimation (ALE) method (Eickhoff et al., 2009; Laird et al., 2005; Turkeltaub et al., 2002) has been applied. The peaks of enhanced activation extracted by all the selected articles were used to create an ALE map, representing the regions engaged for prospection processes. Then, we exploited the ALE method to create distinct ALE maps for each domain of interest, obtaining areas of activation specifically engaged for FT, PM and DD.

This approach aims to identify areas with a convergence of reported coordinates across experiments that is higher than expected from a random spatial distribution. Briefly, the revised ALE algorithm treats activated foci of brain regions as 3D Gaussian probability distributions centered at the given coordinates (Eickhoff et al., 2009; Laird et al., 2005). The size of the probability distributions depends on the sample size of each study. Moreover, the algorithm is based on the random-effect inference, by which the above chance clustering is tested between contrasts and not between foci. Thus, the algorithm tries to outline regions of a particular group of experiments where the likelihood of activation is higher than expected by chance, namely where there is a non-random convergence. Further details on the ALE method are largely explained in the original publications (Eickhoff et al., 2009, 2012; Turkeltaub et al., 2012).

2.3. ALE Discriminability analysis and Conjunction analysis

The ALE method has been used also to compare statistically the ALE maps obtained by the single meta-analyses. We conducted three discriminability analyses to understand whether there were differences in spatial convergence in the direct comparison of each domain to the others. Each analysis yielded brain regions that are specifically activated for FT, PM and DD.

Notably, we contrasted the ALE map of FT with the ALE map derived from the consistency analysis of the peaks of activation of PM and DD (FT ALE map > PM+DD ALE map), the ALE map of PM with the one derived from FT and DD meta-analyses (PM ALE map > DD+FT ALE map), and the ALE map of DD with the one derived from the analysis performed on the pooled coordinates of FT and PM (DD ALE map >

Table 1

List of studies included in the meta-analysis for each domain. Contrasts were grouped based on the compared conditions.

	First Author	Year	N° of subjects	N° of foci	Contrasts					
					Future > past	Future > present	Future > control	Future + past > past	Congruent > Incongruent	Novel > repeat
Future Thinking	Addis	2007	16	18	X					
	Botzung	2008	10	12			X			
	Abraham	2008	20	9	X					
	Szpunar	2009	27	10	X					
	Weiler (a)	2010	32	13			X			
	Weiler (b)	2010	17	6	X					
	Nyberg	2010	5	4				X		
	D'Argembeau	2010	20	9						X
	Martin	2011	25	20			X			
	Van Mulukom	2013	20	10			X			
	Van Hoeck	2013	14	12	X					
	Kirvan	2014	15	8	X					
	Gilmore	2014	21	11	X					
	Szpunar	2014	46	14						X
	Sasse	2015	23	6			X			
	Cascio	2016	67	10	X					
	Gauthier	2016	17	20				X		
	Demblon	2016	23	3					X	
	Roberts	2017	22	6					X	
	Kruschwitz	2018	31	4		X				
Palombo	2018	26	15		X					
Beaty	2018	29	18			X				
Roberts	2020	24	28					X		
Rafei	2021	22	4			X				
Prospective memory	Okuda	1998	6	7	PM + Ongoing task block > Ongoing task block		Encoding of the intention			
	Burgess	2001	8	10	X					
	Burgess	2003	9	1	X					
	Den ouden	2005	11	3	X					
	Simons	2006	16	1	X					
	Eschen	2007	10	6			X			
	Poppenk	2010	13	8			X			
	Kalpuzos	2010	14	16	X					
	Okuda	2011	16	3	X					
	Gilbert	2011	32	7			X			
	Benoit	2011	16	7	X					
	Mc Daniel	2013	45	9	X					
	Beck	2014	47	24	X					
	Wang	2014	22	10	X					
	Gao	2014	13	13	X					
	Beck	2016	60	41	X					
	Peira	2016	15	9	X					
	Chen	2019	38	3	X					
	Koslow	2019	28	29	X					
Delay discounting	Tanaka	2004	20	15	Delay > immediate		Delay discounting > control		Correlation with temporal discount factor	
	Kable	2007	10	1	X					
	Wittmann	2007	13	7	X					
	Weber	2008	23	5	X					
	Loumann	2008	20	6	X					
	Pine	2009	24	22				X		

(continued on next page)

Table 1 (continued)

First Author	Year	N° of subjects	N° of foci	Contrasts				
				Future > past	Future > present	Future > control	Congruent > incongruent	Novel > repeat
Bickel	2009	30	5			X		
Peters	2010	30	13			X		
Wittman	2010	13	2	X				
Benoit	2011	12	25			X		
Christakou	2011	40	11	X				
Spirada	2011	20	15	X				
Murawski	2012	13	13			X		
Luo	2012	21	7	X				
Burton Avsar	2013	14	18			X		
Hare	2014	27	22				X	
Wang	2014	28	7				X	
Waegeman	2014	41	8	X				
Magen	2014	23	8	X				
Koffarnus	2017	18	9	X				
Wang	2017	21	3	X				
O'Connell	2018	36	14	X				
Ikink	2019	24	7	X				
Herman AM	2019	30	6					X
Neukam	2019	90	31					X
Wang (a)	2021	19	7					X
Wang (b)	2021	19	10					X

FT+PM ALE map).

To perform each discriminability analysis, all coordinates of the experiments contributing to the meta-analysis were pooled together and randomly divided into two groups of the same size as the original contrasted sets of data (Eickhoff et al., 2011). Voxel-wise ALE scores of these two randomly assembled groups are subtracted from each other and recorded, recursively for 10,000 times, creating an empirical null distribution of ALE-score differences between the two conditions. Based on this permutation procedure, the map of true differences was then thresholded at a corrected $p < 0.05$. In addition, an extent threshold of 100 voxels was applied to eliminate minor findings.

Finally, we computed a conjunction analysis of the ALE maps coming from the single meta-analyses, by the minimum statistics (Nichols et al., 2005). We used the "Image calculator" function of SPM12 (<http://fil.ion.ucl.ac.uk/spm/>) to compute the voxel-wise minimum across the three thresholded ALE maps. It identified voxels that were significant in all individual analyses, creating a conjunction map of activation of the three domains of interest.

3. Results

3.1. Neural activations of prospection

The first ALE meta-analysis was conducted on the peaks of activation of all the selected articles exploring prospection. It included 783 foci from 70 experiments for a total of 1702 participants. Results revealed significant convergence of activity across all studies in different brain regions that include (see Table 2, Fig. 1):

1. Medial part of anterior prefrontal cortex (aPFC; BA 10) in the left hemisphere;
2. Lateral part of left aPFC and dorsolateral prefrontal cortex (DLPFC) (BA 10 and BA 46);
3. Left regions in the middle and inferior frontal gyri (IFG) at the intersection between Brodman Areas 44 (pars opercularis), 6 and 9;
4. Bilateral insular cortex (BA 13);
5. Posterior cingulate cortex and precuneus in the left hemisphere (PCC; BA 23, 31);
6. Left regions in the angular gyrus, in the posterior division of inferior parietal lobule and over lateral occipital cortex (IPL; BA 39, 19).

3.2. Individual meta-analyses and discriminability analyses

In order to define the loci of activation specific for FT, PM and DD, a single meta-analysis was conducted for each domain. Moreover, we decided to contrast each ALE map to the others, to find neural dissociations across them.

3.2.1. Neural activations of FT

The meta-analysis on FT included 277 foci from 24 experiments for a total of 608 participants. Results showed significant convergence of activation in different areas exclusively located in the left hemisphere (see Table 3, Fig. 2). These included the medial part of the aPFC (BA 9,10), the PCC extending to precuneus (BA 31, 23), parietal regions that include IPL, angular gyrus and intraparietal sulcus (BA 39), superior occipital gyrus (BA 19), and portions of middle and inferior temporal gyri (BA 21, 20). The same regions were identified when contrasting FT with PM and DD.

3.2.2. Neural activations of PM

The meta-analysis on PM included 208 foci from 19 experiments for a total of 422 participants. As can be seen in Fig. 2, areas activated by PM tasks were located in portions of the left pre supplementary motor area (pre SMA; BA 6) extending to ACC and frontal eye fields (FEF; BA 8), posterior cingulate area (posterior cingulate gyrus extending to PCC, BA 23, 31), the right insular cortex (BA 13) and part of the right

Table 2
Locations of clusters of activation in Prospection.

Cluster size	MNI coordinates			Brain region	Brodmann Area	ALE extrema value
	x	y	z			
3840	-4	-58	26	Posterior Cingulate Cortex	23	0.042571854
	0	-28	32	Posterior Cingulate Gyrus	23	0.02904803
	-6	-46	32	Precuneus	31	0.028647423
3024	-44	-68	32	Angular Gyrus	39	0.040035333
	-42	-64	44	Posterior Inferior Parietal Lobule	39	0.02801951
	-36	-80	36	Superior Occipital Gyrus	19	0.022926921
	-34	18	-4	Clastrum	/	0.03376034
1008	36	24	-2	Insula	13	0.033671893
944	-42	8	34	Middle and Inferior Frontal Gyri	44/6/9	0.029336652
864	-6	58	-4	Medial Frontal Gyrus	10	0.02475619
840	-10	62	6	Medial Frontal Gyrus	10	0.023464989
	-48	40	4	Lateral Prefrontal Cortex	46	0.026710207
776	-40	48	10	DorsoLateral Prefrontal Cortex	10	0.01842604

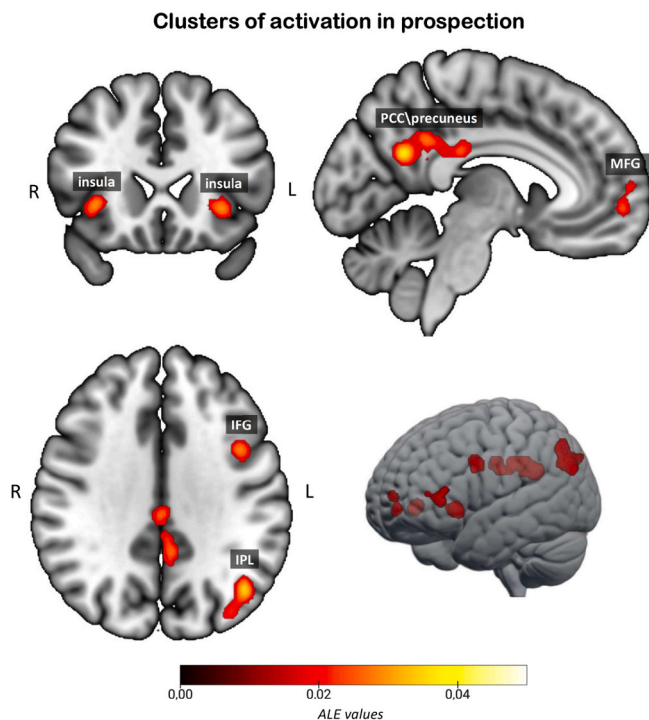


Fig. 1. Neural activations of prospection. Brain regions activated by all tasks requiring future prospection. The color bar indicates the ALE values for each voxel, where yellow represents the most significant ones within the cluster. PCC = posterior cingulate cortex; MFG = medial frontal gyrus; IFG = inferior frontal gyrus; IPL = inferior parietal lobule.

orbitofrontal cortex (OFC; BA 47)..

Contrasting the activations pattern of PM with FT and DD, the aforementioned areas still showed significant activation.

3.2.3. Neural activations of DD

The meta-analysis on DD included 298 foci from 27 experiments for a total of 672 participants. It revealed a consistent association with three main clusters of activation (see Table 3, Fig. 2). In the left hemisphere, it was found a consistent activation of insular cortex (BA 13) extending to the OFC, pars triangularis of the inferior frontal gyrus and frontal pole. In the right hemisphere, regions of the inferior frontal gyrus (pars opercularis) and DLPFC (BA 9) and the middle frontal gyrus (BA 8) were shown to be activated. The same clusters emerged by the comparison of DD with the other two domains.

3.3. Conjunction analysis

In order to identify common areas of activation between FT, PM and DD, we conducted a conjunction analysis of the individual thresholded maps. Based on it, no significant cluster emerged.

4. Discussion

4.1. Neural basis of prospection

Prospection is defined as 'the ability to represent what might happen in the future' (Szpunar et al., 2014; see also Buckner and Carroll, 2007) and encompasses a series of future-oriented cognitions that can be clustered under the names Future Thinking (FT), Prospective Memory (PM), and Delay Discounting (DD) (Szpunar et al., 2014). Building upon this taxonomy and framework of prospection, we conducted an Activation Likelihood Estimation (ALE) meta-analysis to investigate possible shared and distinct brain activations underlying these three future-related functions. By considering the three functions within the same meta-analysis, we aimed to uncover the neural correlates that contribute to the overall understanding of prospection.

More specifically, the first aim was indeed to delineate a general overview of what are the brain regions that are consistently activated across the studies of prospection (i.e., studies of FT, PM and DD), regardless of the type of task/activity. We have found the involvement of regions belonging to two main networks: the Default Network (Raichle et al., 2001) and the Salience Network (Seeley et al., 2007). More specifically, a consistent Default Network activation involved medial aPFC and posterior regions in the lateral and medial parietal cortex (i.e., PCC and precuneus). A consistent Salience Network activation instead involved bilateral insulae and inferior frontal gyrus (but not anterior cingulate cortex).

Interestingly, such activations were leftward lateralized for all the brain structures but insulae, which were bilaterally recruited. A possible explanation that accounts for the left lateralization of prospection is related to the fact that the left hemisphere is specialized for language processing (Corballis, 2021; Häberling et al., 2016; Hellige, 1993). Therefore, it may be particularly recruited during prospection for the creation of verbal and linguistic representations that are useful to generate mental scenarios and predictions about future events.

Another possible explanation for the activation of the left hemisphere is that prospection relies upon retrieving relevant autobiographical memories and experiences from the past to make inferences about the future (Schacter and Addis, 2007b). Autobiographical memory is mediated by a neural network of left-lateralized regions (Karolis et al., 2019) including the medial and ventrolateral PFC, medial and lateral temporal regions and retrosplenial/PCC, the temporoparietal junction and the cerebellum (Svoboda et al., 2006) - most of which are

Table 3

Locations of clusters of activation in each future-related domain, derived by consistency and discriminability analysis.

	Cluster size	MNI coordinates			Brain region	Brodmann Area	ALE maxima value
		x	y	z			
FT	2480	-44	-68	32	Inferior Parietal Lobule\Angular Gyrus	39	0.03120948
		-38	-76	34	Superior Occipital Gyrus	19	0.01791233
	2368	-4	-58	26	Posterior Cingulate Cortex	31	0.033183683
		-6	-46	32	Precuneus	23\31	0.022928426
	1256	-62	-12	-12	Middle and Inferior Temporal Gyri	21\20	0.024875078
	704	-6	60	20	Medial Frontal Gyrus	9	0.018868491
		-6	62	8	Medial Frontal Gyrus	10	0.016909001
FT > PM + DD	2096	-45.5	-72	31.5	Middle Temporal Gyrus	39	
	1872	0	-56	32	Posterior Cingulate Gyrus	31	
		0	-62	26	Precuneus	23	
	1256	-61.2	-8.7	-16.9	Inferior Temporal Gyrus	21	
		-64	-12.5	-11	Middle Temporal Gyrus	21	
	408	-6	57	18	Medial Frontal Gyrus	9	
		-6	62	18	Superior Frontal Gyrus	9	
		-6	60	14	Superior Frontal Gyrus	9	
PM	880	2	-26	30	Posterior Cingulate Gyrus	23\31	0.01797472
	728	-4	24	46	Pre-Supplementary Motor Area\Frontal Eye Fields	6\8	0.022642937
	696	36	24	-4	Insula\Orbitofrontal Cortex	13\47	0.019643566
PM > FT + DD	608	-2	20	44	Medial Frontal Gyrus	6	
		-4	24	46	Medial Frontal Gyrus	6	
	528	4	-22	27.5	Posterior Cingulate Gyrus	23	
	328	36	22	-8	Insula	13	
DD	816	50	14	28	Inferior Frontal Gyrus (pars opercularis)\Middle Frontal Gyrus	8\9	0.0263718
	768	-32	20	0	Insula	13	0.018068071
	752	-48	38	2	Inferior Frontal Gyrus (pars triangularis)\Dorsolateral Prefrontal Cortex	46	0.022183876
DD > FT + PM	592	54	12	30	Inferior Frontal Gyrus	9	
		50	14	24	Inferior Frontal Gyrus	9	
	568	-48	42	0	Inferior Frontal Gyrus	46	
		-46	36	-2	Inferior Frontal Gyrus	45	
	360	-28	22	2	Insula	13	

Abbreviations: FT = Future Thinking; PM = Prospective memory; DD = Delay Discounting.

shared with future thinking.

The second – and main – aim of the study was testing the hypothesis whether a core “network of the future” exists, namely there is a common set of brain activations across FT, PM and DD, or whether the three domains depend on distinct circuits. To do so, we ran a conjunction analysis. This analysis revealed no overlapping activation between FT, PM and DD, suggesting that the three domains rely upon separate brain regions. Thus, processing of the future representations is strictly related to the task or activity required and implies different neurocognitive mechanisms.

4.2. Neural basis of future thinking

The meta-analysis on FT revealed activations distributed only in the left hemisphere and included medial regions of aPFC, PCC and precuneus, lateral regions in parietal lobe (IPL, angular gyrus and intraparietal sulcus), superior occipital regions and portions of middle and inferior temporal gyrus. Importantly, these regions are specific and unique for FT, since emerged also when contrasting FT with PM and DD.

This pattern of findings confirms a key role of the Default Network – which comprises medial aPFC, PCC and Precuneus, IPL – in the act to project oneself into future scenarios (Benoit and Schacter, 2015; Schacter et al., 2017; Stawarczyk et al., 2018). Previous studies found involvement of the Default Network in internally self-generated thoughts, mentalizing, and remembering (e.g., Addis et al., 2009; Stawarczyk et al., 2018) suggesting that FT is at least partially mediated by these processes.

In particular, the constructive episodic simulation hypothesis posits that we imagine future scenarios in part by retrieving episodic details and proposes that the identified Default Network supports processes related to both remembering the past and imagining hypothetical, future events (Schacter and Addis, 2007a). Beside the mnemonic component of FT, other processes mediate the activity of imagining the future. The Default Network was indeed shown to be composed of three different components (Andrews-Hanna et al., 2010): a dorsal-medial network is predominantly engaged for self-referential processing, whereas a medial temporal network becomes preferentially engaged for imagining a situation. The mPFC and PCC are instead involved in both processes (future self and present self).

As compared with other studies, however, we did not find activation over hippocampal and parahippocampal regions. Among the 24 studies included in the analysis, only seven articles showed contrasts that lead to convergence of activation of hippocampus/parahippocampus. There could be several explanations of this. The first and main explanation is based on the contrast included in the meta-analysis. We selected contrasts that mostly represent and emphasize the process of envisioning the future in the FT tasks. It is thus possible that hippocampal and parahippocampal activations are more involved in other types of contrasts.

Another explanation is related to the studies included. For example, some studies (e.g., Addis et al., 2007, 2011) found activation of the hippocampus only in the ROI analysis and not in the whole brain analysis. Based on our exclusion criteria, we excluded the clusters of activations derived from the ROI analysis.

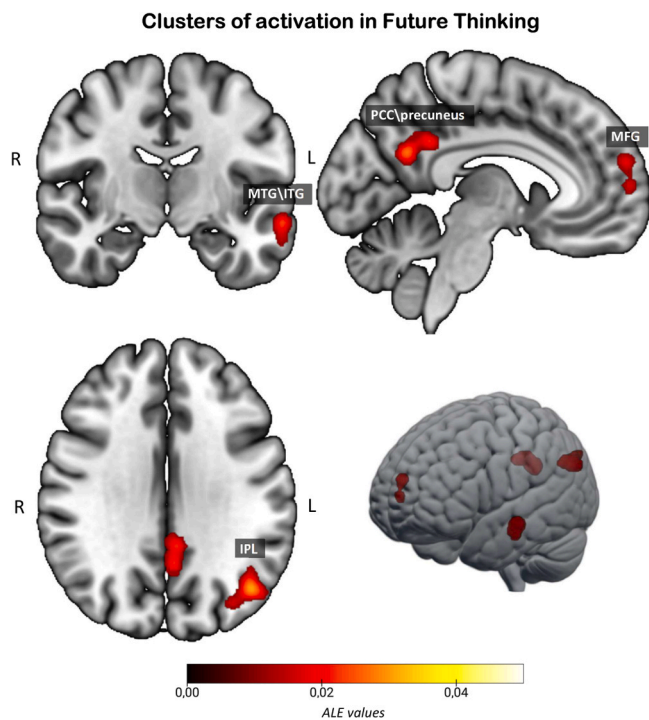


Fig. 2. Neural activations of FT. Brain regions activated by tasks requiring imagination of future perspectives. The color bar indicates the ALE values for each voxel, where yellow represents the most significant ones within the cluster. The same brain regions were revealed by the contrast analysis of FT with PM and DD. MTG = medial temporal gyrus; ITG = inferior temporal gyrus; PCC = posterior cingulate cortex; MFG = medial frontal gyrus; IPL = inferior parietal lobule.

4.3. Neural basis of the future in the prospective memory

When considering the brain regions associated with the representation of the future in PM tasks, consistent activations of right insula and right orbitofrontal cortex, left pre-supplementary motor area extending to part of anterior cingulate/paracingulate cortex, and posterior cingulate regions were found. Interestingly, most of these regions are part of the ‘Salience Network’, which is anchored in orbital frontoinsula and includes anterior cingulate cortex and part of supplementary motor area (Seeley et al., 2007; Touroutoglou et al., 2012).

The Salience Network is deputed to identify subjectively relevant (internal or external) stimuli in order to drive the behavior (Menon and Uddin, 2010; Uddin, 2015). In PM paradigms, the Salience Network is involved in encoding, monitoring, and detecting cues that signal the need for executing an action in the future, and in maintaining attention until the future intended action is performed. The network also plays a role in inhibiting ongoing actions and switching attention to the internal representation of future intention when the appropriate cue is detected (Cona et al., 2015).

The study by Halahalli et al. (2015) found a widespread and robust activation of the dorsal anterior insula and other brain regions that compose the Salience Network during and ‘endogenous-cue prospective memory task’, suggesting the critical role of these regions in the performance of tasks that involve maintaining and updating the representation of future intentions. Interestingly, a recent study showed that alterations in the Salience Network are associated with lower PM performance in elderly (Morand et al., 2022), supporting the view of a critical role of Salience Network in PM.

The Salience Network is interconnected with both the Default Network and the Frontoparietal Central Executive network and acts as a

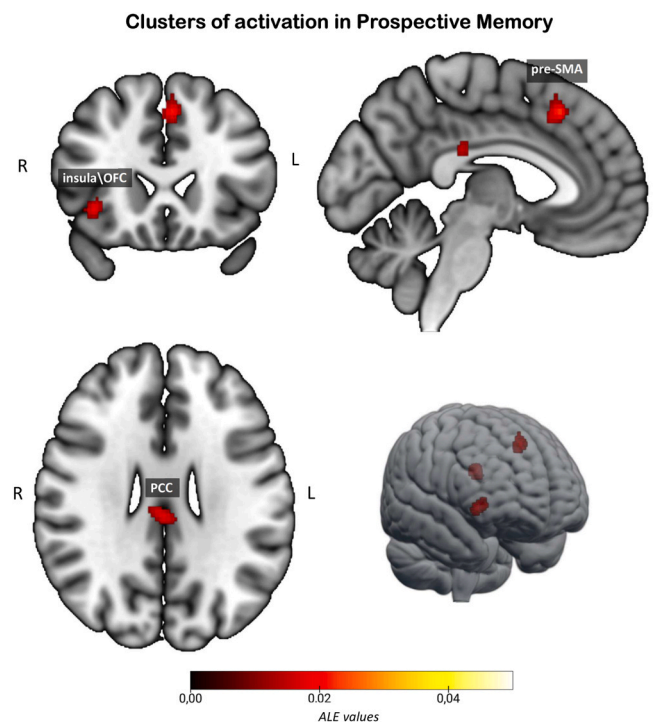


Fig. 3. Neural activations of PM. Brain regions activated by tasks requiring imagination of future perspectives. The color bar indicates the ALE values for each voxel, where yellow represents the most significant ones within the cluster. The same brain regions were revealed by the contrast analysis of PM with FT and DD. OFC = orbitofrontal cortex; pre-SMA = pre-supplementary motor area; PCC = posterior cingulate cortex.

switch between the two networks (Goulden et al., 2014; Sridharan et al., 2008). The interaction of the Salience Network with the other two networks makes the Salience Network the best candidate for shifting attention between external and internal processes (Menon, 2011; Seeley et al., 2007). As evidenced in a recent model – the Attention to Delayed Intention (AtoDI model, Cona et al., 2015, 2016), PM represents a bridge between externally directed processes (e.g., attention to the ongoing activity, monitoring the PM stimuli in the environment) and internally directed processes (i.e., encoding, maintaining and retrieving the future intention). Thus, an efficient Salience Network and a good functional coupling with the Default Network and Central executive Network mediate important functions in PM. In support to this, together with the Salience Network, regions of posterior cingulate gyrus and posterior cingulate cortex – although more dorsally located as compared with the PCC activations shown in FT - were found to be consistently activated in PM. The PCC is a major node within the Default Network and has many structural connections to other brain regions, indicating a role as a cortical hub (Hagmann et al., 2008). Several lines of research showed the PCC interacts with other networks to regulate the balance between externally and internally directed cognition (Leech et al., 2012). In PM research, the formation of the future intention has been related to PCC activation also in the study by Gilbert et al. (2007). Finally, the pre-SMA was found consistently activated in PM tasks. According to the AtoDi model, the pre-SMA and SMA would integrate multiple information to implement the future action (Cona et al., 2015). As the PCC, the SMA regions act as hubs, receiving and integrating information from different motor and sensory regions sequential elements into higher-order representations regardless of the nature of such elements (e.g., spatial, motor, temporal, numerical, linguistic, etc.) (Cona and Semenza, 2017, for a review).

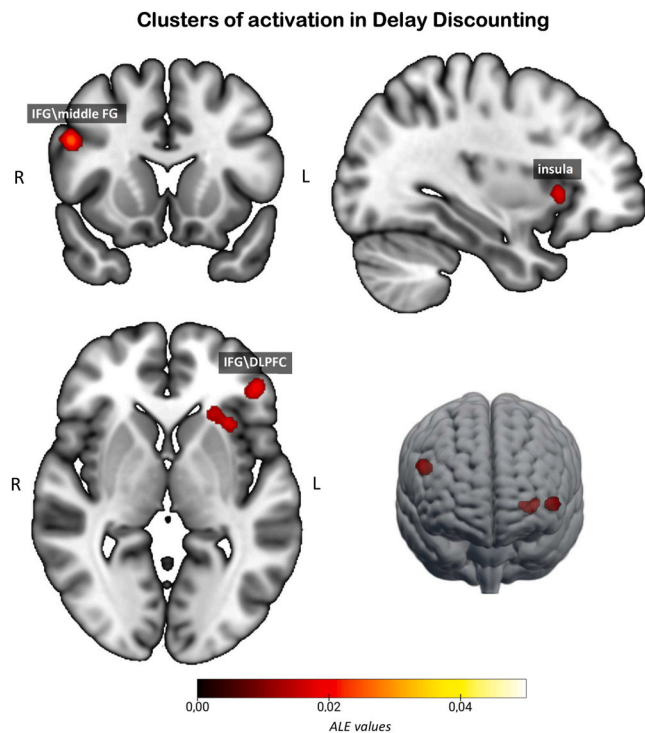


Fig. 4. Neural activations of DD. Brain regions activated by tasks requiring imagination of future perspectives. The color bar indicates the ALE values for each voxel, where yellow represents the most significant ones within the cluster. The same brain regions were revealed by the contrast analysis of DD with PM and FT. IFG = inferior frontal gyrus; FG = frontal gyrus; DLPFC = dorsolateral prefrontal cortex.

4.4. Neural basis of the future in the delay discounting

The meta-analysis on DD revealed consistent activation of the left insula, left IFG (pars triangularis) and frontal pole, and right frontal regions comprising IFG (pars opercularis) and part of DLPFC. These regions emerged also when contrasting DD with the other two domains, indicating a specific contribution of them in DD.

As for PM, simulating future outcomes in the DD tasks (i.e., future rewards) relies upon regions of the Salience Network (i.e., insula and IFG), although in the left hemisphere. Interestingly, several researches showed that Salience Network at rest can predict the individual delay discounting of reward (Chen et al., 2017; Yang et al., 2022) and alteration in the Salience Network have been associated with steeper DD in smokers (Clewett et al., 2014) and alcohol dependent individuals (Grodin et al., 2017). Notably, a recent study showed the activation of the Salience Network during the anticipation of both rewards and losses (Pinger et al., 2022). This corroborates the idea of a pivotal involvement of Salience Network in forming future representations (either rewards or losses) during inter-temporal decision making.

In our meta-analysis, however, we did not find consistent activation of the ACC, which is a region of the Salience Network, but only activation of left insula and left IFG. This probably suggests that the process of evaluating and comparing inter-temporal options (present vs future option) is mainly mediated by fronto-insular cortex and depend less on the activity in the ACC.

The left IFG and insula emerged also in the meta-analysis by Schüller and collaborators (2019), indicating that these regions support the preference for delayed choice in healthy individuals. Importantly, the meta-analysis by Schüller et al. (2019) revealed that the decreased activity of left IFG is a key brain marker of the alterations in DD observed in patients with substance use disorder (i.e., less preference for delayed choice).

Clusters of functional overlap over left frontal regions (IFG and posterior portion of the left lateral PFC) were also found between DD and working memory in a meta-analysis by Wesley and Bickel (2014). Based on the shared activations, the authors hypothesized a contribution of these frontal regions in executive processes and, more particularly, in integrating information about the past and the foreseeable future to implement executive processes while making decisions. The results of our meta-analysis give further support to this hypothesis, indicating a possible functional meaning of left frontal activation with processing of temporal representation.

Of particular relevance to the current study, a recent meta-analysis examined whether larger delayed rewards (referred to as 'LargerLater' in the article) versus smaller, sooner rewards ('SmallerSooner') were associated with distinct prefrontal regions arranged in a posterior-anterior gradient (Smith et al., 2018). This prediction is based on the concept of a prefrontal cortex 'abstraction hierarchy,' positing that abstract representations are coded in more anterior regions, while concrete representations are coded in more posterior regions. In the delayed discounting (DD) tasks, selecting the LargerLater reward is linked to the more abstract representation of contextual factors (such as personal goals and events), whereas choosing a near-reward is associated with a more concrete context (e.g., specific goals, events, and rewards). In line with this prediction, an anterior-posterior tangibility axis was found over the left IFG regions where activations related to LargerLater were located more anteriorly than SmallerSooner activations. This pattern of results corroborates our finding of a role of the pars triangularis of left IFG in representing and simulating the future, which is intrinsically abstract.

4.5. Differences in the neurocognitive mechanisms among the three future-oriented cognitions

The conjunction analysis revealed that there is no overlapping activation between FT, PM and DD, thus there is no specific region or network exclusively dedicated to processing the future.

Rather, when examining the pattern of activations across the three future-oriented cognitions, an anterior-posterior gradient can be observed over frontal regions, which can be attributed to the abstraction hierarchy (see Fig. 5). Specifically, among the three cognitions, Future Thinking (FT) tasks involve simulating the most abstract future scenarios, such as imagining a holiday or a birthday party, and are associated with activations in the most anterior regions of the prefrontal cortex (PFC). On the other hand, Delay Discounting (DD) paradigms involve imagining relatively more concrete future rewards, typically monetary in nature, and activate more posterior regions. Finally, Prospective Memory (PM) paradigms, particularly in neuroimaging research, entail simulating very concrete intentions, such as moving the index finger to press a key, and are associated with activations in the most posterior frontal regions.

The representation of the 'future' appears to follow an anterior-posterior tangibility gradient depending on the level of abstractness or concreteness of the scenario being simulated. This observation aligns with the prospection framework proposed by Szpunar and colleagues (2014), which emphasizes the importance of considering levels of abstraction and complexity in distinguishing between different types of future-related modes and tasks.

Furthermore, our findings indicate that prospection is mediated by two distinct networks: the Default Network and the Salience Network. Specifically, the Default Network plays a primary role in supporting Future Thinking (FT), while the Salience Network is primarily involved in Prospective Memory (PM) and Delay Discounting (DD) tasks. One potential difference that may account for this dissociation lies in how these activities rely on external versus internal stimuli. In FT paradigms, the brain combines information and memories to construct internal models of future events, thus engaging the Default Network, which is less dependent on external stimuli. This is in line with the review by

Activations in future-related domains

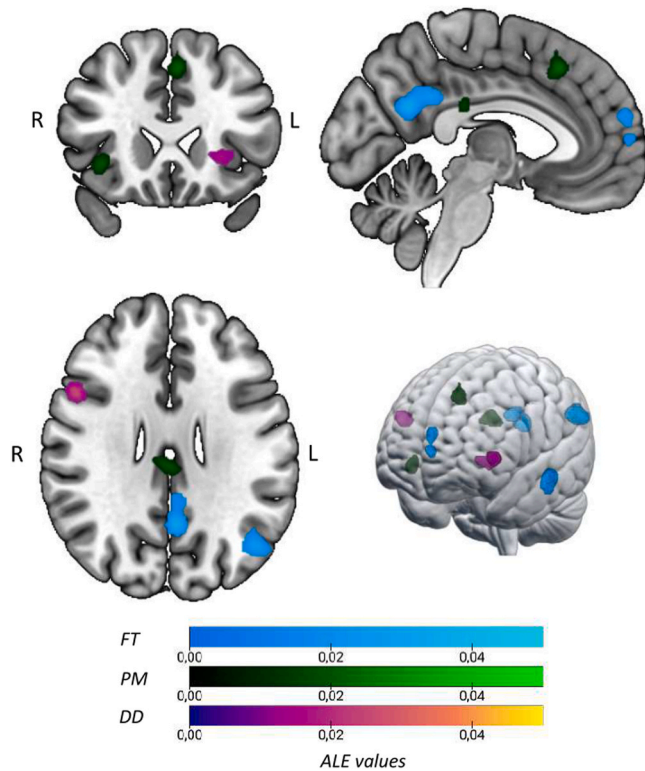


Fig. 5. Neural activations of FT (blue), PM (green) and DD (purple). Conjunction analysis showed no overlap among the three ALE maps.

Kvavilashvili and Rummel (2020), which demonstrates that individuals often contemplate their future through spontaneous thoughts that arise during mind-wandering periods when they are not entirely focused on a task.

In contrast, both PM and DD paradigms require interaction with the external environment. PM tasks involve monitoring the presence of PM cues, while DD tasks involve comparing the amount of money between two options. The Salience Network is activated in PM and DD tasks as it is recruited for attentional processes and the selection of relevant stimuli or events in the environment, amidst multiple competing internal and external stimuli (Uddin, 2015).

The third main difference among the three functions pertains to the dimension of 'future'. The temporal scales of future processing can vary significantly across paradigms. However, it is important to note that this meta-analysis cannot definitively answer the question of temporal scale, as it may also vary within the same paradigm. Therefore, future studies should specifically focus on investigating this issue. Defining the concept of 'future' itself presents challenges, as beautifully expressed in the poem by Wisława Szymborska: 'When I pronounce the word Future, the first syllable already belongs to the past'.

Declaration of Competing Interest

None.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.neubiorev.2023.105355](https://doi.org/10.1016/j.neubiorev.2023.105355).

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