



A meta-analytical review of brain activity associated with intertemporal decisions: Evidence for an anterior-posterior tangibility axis

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ABSTRACT

In temporal discounting experiments, subjects are repeatedly presented with option sets in which they must choose between receiving a small amount of money sooner (SmallerSooner) or a larger amount of money at a more distant point in time (LargerLater). Although over 50 temporal discounting experiments using fMRI are described in literature, there has not been a meta-analysis identifying regions activated when subjects choose SmallerSooner versus LargerLater alternatives. Evidence suggests a prefrontal cortex 'abstraction hierarchy', from abstract planning in more anterior regions to concrete processing in posterior regions. Because abstraction has been linked with making LargerLater choices, we hypothesized an association between LargerLater choices and more anterior prefrontal cortex activity, and an association between SmallerSooner choices and more posterior activity. Across thirteen fMRI temporal discounting studies including 436 subjects, we observed LargerLater activity anterior of SmallerSooner activity, both in the left inferior frontal gyrus pars triangularis, consistent with our pre-registered hypothesis. We call for further work linking temporal discounting and hierarchical processing of abstract and concrete information in the prefrontal cortex.

1. Introduction

A wide variety of critical decisions, including those related to health, to financial security, and to education, depend on people's ability to go beyond the present and consider the future. Because of this, decision scientists have long been interested in understanding how temporal distance affects the value people assign to competing options (Mischel et al., 1989). A robust body of findings suggest that people generally underweight the future. Available rewards tend to be less valued (as inferred through preference) when they are temporally distant. Moreover, the degree to which individuals discount distant compared to near rewards has been shown to predict a wide array of behavioral problems, including pathological gambling (Ledgerwood et al., 2014), poor health behavior (Dong et al., 2016), overeating (Bickel et al., 2012) and saving (Laibson, 1997). Decision neuroscientists have sought to understand the neural substrates of temporal discounting (e.g., Kable & Glimcher, 2007; McClure et al., 2004). Here, we integrate prior findings to explore neural differences associated with selections made between choosing a smaller monetary amount sooner ("Smaller-Sooner decisions") or a larger amount later ("LargerLater decisions"). Given that temporal discounting appears to be related to the tendency

for people to construe immediate events more concretely than temporally distant ones (O'Connor et al., 2012; Peters & Büchel, 2010; Yi et al., 2017), we also seek to connect this work on intertemporal choice to a more general theory of how abstract information is processed in the brain.

A large number of papers explore the neuroscience of temporal discounting using functional Magnetic Resonance Imaging (fMRI). One important meta-analytic review was published in 2010 by Carter and colleagues (Carter et al., 2010). However, since then, over 140 published articles have examined applications or the theoretical bases of intertemporal choice (see Appendix 1 in the Supplemental online materials). Recent conceptual reviews of this literature (Moreira et al., 2016; Scheres et al., 2013; Wesley & Bickel, 2014) broadly consider the neurological basis for temporal discounting, but none have sought to examine differences in activity associated with SmallerSooner and LargerLater selections. The current meta-analysis therefore aims to fill this gap. Specifically, we sought to use available published reports to identify differentiation between brain activity during selection of SmallerSooner vs. selection of LargerLater options. We do so with a particular hypothesis in mind: that LargerLater options will be associated with activity of more anterior regions of the prefrontal cortex

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than selection of SmallerSooner options. As developed below, we base this prediction on two key literatures: research on construal level theory (CLT) connecting abstraction with LargerLater choices (O'Connor et al., 2012; Peters & Büchel, 2010; Yi et al., 2017), and research on the structure of the prefrontal cortex suggesting an anterior-posterior axis of tangibility (Badre & D'Esposito, 2009; Bechara & Damasio, 2005; Botvinick et al., 2009).

1.1. Temporal discounting, construal-level theory, and the prefrontal tangibility axis

Construal Level Theory (CLT; Trope and Liberman, 2010) is a social-psychological framework centered on the idea that representations of objects or events vary in their level of construal, or degree of abstraction. High-level construals are abstract and structured cognitive representations that emphasize an event's superordinate and defining features. By contrast, low-level construal are concrete and contextualized representations that include an emphasis on subordinate details. Importantly, CLT argues that delay is a potent determinant of psychological distance, and consequently, of construal level. Events anticipated in the more distant future tend to evoke high-level construals, while those near evoke lower-level construals. An important implication of this is that construal-level for the very same event will predictably shift from high- to low-level, with the mere passage of time. For example, an academic might think about an opportunity to give a talk abstractly when it is months away, focusing on its relation to superordinate goals like scientific engagement and career advancement. As that same talk becomes close in time, the high-level construal may yield to increased representation of concrete lower-level features, including the hassles of travel and lost time that could otherwise be directed at obligations. And with that shift in construal-level, the appeal of the event can change. Given the strong connection between delay and construal level, it is possible that the two options of a typical delay discounting questions (e.g., "Would you prefer \$10 today or \$15 in one month?") tend to evoke asymmetric construal levels, with higher level construals for the more delayed options (see Trope and Liberman, 2003, for an in-depth discussion of the link between CLT and the extant discounting literature).

Early work on delay discounting was rooted in the logical positivist traditions of economics and behaviorism, and was thus agnostic on underlying mechanism (Herrnstein, 1961; Strotz, 1955). As the construct of delay discounting has been incorporated into social psychology and cognitive neuroscience, questions of mediating mechanisms have come to the foreground. CLT provides one, we think compelling, partial account of the psychological mechanism by which delay affects preference. While delay contributes to construal level, it does not fully determine it. Rather, the construal level at which an event, outcome, or even decision is represented can be influenced by a number of contextual factors, including prior exposure to procedures that evoke a "high-level" or "low-level" mindset or processing orientation. This is important because construal level mindsets can affect preferences between more and less delayed alternatives, including those presented in delay discounting tasks. Construal theorists have argued that an abstract mindset facilitates a more high-level focus on goal-relevant and top-down features while a concrete mindset promotes sensitivity to concrete and visceral aspects of a stimulus (Carnevale et al., 2015; Fujita & Han, 2009). In line with this, research has found that people's delay discounting choices are systematically influenced by whether they are prompted to adopt a high-level or low-level cognitive orientation. People encouraged to think abstractly tend to choose the distant future option more than those who are encouraged to think concretely. For example, Fujita et al. (2006) showed that a why (abstract construal) vs. how (concrete construal) manipulation (Vallacher & Wegner, 1987) reduced subjects' delay discounting, an effect conceptually replicated by Malkoc et al. (2010); Maglio et al. (2014), and Rudzinska-Wojciechowska (2017). Yi et al. (2017) also conceptually

replicated this finding; notably, they observed an effect of construal-level on discounting while using a version of the computerized monetary delay discounting task used by all of the studies included in the current meta-analysis.

The link between LargerLater reward selection and abstraction on the one hand, and SmallerSooner reward selection and concretization on the other, hints at a possible neurocognitive mechanism for temporal discounting: a posterior-anterior gradient of increasingly abstract representation, observed (Kringelbach & Rolls, 2004) and discussed (Botvinick et al., 2009) in prior literature. Posterior regions are more closely connected to subcortical reward regions, the somatosensory cortex, and other sensory regions. Conversely, concrete representations of reward, sensations, and activity in those posterior regions are combined and represented more abstractly – according to higher-order goals – in more anterior regions (Badre & D'Esposito, 2009; Botvinick, 2008; Koechlin & Summerfield, 2007). If LargerLater reward selection is associated with more abstract thinking than SmallerSooner reward selection, LargerLater selections may be associated with relatively more anterior prefrontal cortex activity, and SmallerSooner selections with relatively more posterior prefrontal cortex activity.

Existing literature might shed light on neurocognitive processes engaged during temporal discounting, and in particular, on the mechanisms suggested by CLT. The anterior-posterior tangibility axis may be linked to temporal discounting through action control, goals, and domain specificity. Actions (Badre, 2008; Badre & D'Esposito, 2009; Christoff & Gabrieli, 2000; Koechlin & Jubault, 2006), goals (Botvinick, 2008; Koechlin & Summerfield, 2007), and domain specificity (Badre & D'Esposito, 2009) are perceived within hierarchical prefrontal cortex structures in gradients from more concrete nearer to the motor cortex to more abstract in the frontal pole, consistent with the notion of a more general posterior-anterior tangibility axis. When participants in a discounting task focus on the sensory associations of spending the money, they are more likely to make a SmallerSooner selection. By contrast, when participants do not focus on the sensory associations of spending the money, they are not driven to take the SmallerSooner selection; instead an abstract representation leads to a judgment that the LargerLater amount is more worthwhile. Indeed, prior findings suggest that paying attention to tangible visual information about immediate rewards – i.e., thinking highly concretely – is associated with making SmallerSooner choices (O'Connor et al., 2012). Thus, the more concrete thoughts associated with choice of a near-reward (e.g., concrete goals, concrete event construal, concrete reward construal, etc.) should manifest in a stronger posterior prefrontal cortex representation in those choices. Conversely, participants making a LargerLater selection are those who are construing the context (i.e., the goal, event, reward, etc.) more abstractly, and we therefore expect a stronger anterior prefrontal cortex representation in those choices.

We note, however, that it is also plausible to predict the reverse effect. Specifically, if thinking concretely about a LargerLater choice leads to its selection (e.g., Peters & Büchel, 2010), it is possible that anterior activity may actually reflect SmallerSooner rather than LargerLater activity. The reverse effect was not anticipated in advance of investigation, and so is not listed as a "pre-registered hypothesis" with our other hypotheses. Nevertheless, the present study may be treated as a test comparing these two opposing hypotheses.

1.2. Main hypotheses

The hypothesis linking CLT and an anterior-posterior tangibility axis in temporal discounting tasks was preregistered on the Open Science Framework at <https://osf.io/jj8vb/> after the initial literature search, before analysis had begun. Following registration, but before any analysis, we deviated in one important way from the pre-registration. Although we had said we would only do a limited Google Search (described in the pre-registration), we realized after performing this search that this method missed too many studies that clearly ought to be

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