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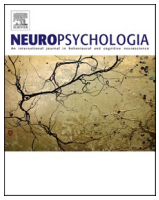

The sign effect in temporal discounting does not require the hippocampus

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ABSTRACT

When considering future outcomes, humans tend to discount gains more than losses. This phenomenon, referred to as the temporal discounting sign effect, is thought to result from the greater anticipated emotional impact of waiting for a negative outcome (dread) compared to waiting for a positive outcome (mixture of savoring and impatience). The impact of such anticipatory emotions has been proposed to rely on episodic future thinking. We evaluated this proposal by examining the presence and magnitude of a sign effect in the intertemporal decisions of individuals with hippocampal amnesia, who are severely impaired in their ability to engage in episodic mental simulation, and by comparing their patterns of choices to those of healthy controls. We also measured loss aversion, the tendency to assign greater value to losses compared to equivalent gains, to verify that any reduction in the sign effect in the hippocampal lesion group could not be explained by a group difference in loss aversion. Results showed that participants with hippocampal amnesia exhibited a sign effect, with less discounting of monetary losses compared to gains, that was similar in magnitude to that of controls. Loss aversion, albeit greater in the hippocampal compared to the control group, did not account for the sign effect. These results indicate that the sign effect does not depend on the integrity of hippocampally mediated episodic processes. They suggest instead that the impact of anticipatory emotions can be factored into decisions via semantic future thinking, drawing on non-contextual knowledge about oneself.

Temporal Discounting (TD) refers to the depreciation of the subjective value of rewards as their realization is deferred further into the future (Ainslie, 1975; Frederick et al., 2002; Green and Myerson, 1993; Logue, 1988). This mental computation is critical to a variety of daily decisions, such as consumer preferences (Lynch and Zauberman, 2006), planning the timing of retirement (Bidewell et al., 2006), environmental choices (Hardisty and Weber, 2009; Polasky and Dampha, 2021), and substance use and health behaviors (Bickel et al., 2014, 2019; Story et al., 2014). TD has been observed for decisions with both positive and negative outcomes (Denburg and Hedgcock, 2015). For positive outcomes, TD manifests as preference for a smaller immediate reward over a larger delayed one (e.g., choosing to receive $80 now rather than $100 in a year). Namely, there is a desire to accelerate positive events to the present, as seen in individuals opting to spend retirement funds today rather than conserving them for future financial security (Lynch and Zauberman, 2006). For negative outcomes, TD manifests as preference for a larger later loss over a smaller immediate loss (e.g., choosing to lose $100 in a year rather than $80 now). In other words, there is a desire to postpone losses, as is apparent in decisions to delay credit card reimbursement (Meier and Sprenger, 2010) or postpone mortgage payments (Atlas et al., 2017).

Several factors similarly influence TD of positive and negative outcomes. These factors include basic economics principles, by which a smaller amount of money now may have greater economic value than a larger sum in five years, as it can be invested for interest and has not yet undergone inflation (e.g., Ostaszewski et al., 1998); a conceptualization of the future as psychologically distant, with consideration that the gain or loss may not actually happen (e.g., Croote et al., 2020; Urminsky, 2017; M. Zhang and Aggarwal, 2015); and personality factors such as trait impulsivity (Moreira and Barbosa, 2019).

Positive and negative events, however, are not discounted equally. There is compelling evidence for the presence of a sign effect (Thaler, 1981) whereby losses tend to be discounted less than gains (Baker et al., 2003; Estle et al., 2006; Hardisty and Weber, 2009; Murphy et al., 2001; Ruggeri et al., 2022). In other words, the wish to postpone a negative outcome tends to be less potent than the wish to immediately realize a positive outcome. The sign effect has been linked with significant social and health problems, such as obesity (Ikeda et al., 2010) or cigarette

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smoking (Odum et al., 2002), but despite its relevance, questions remain regarding the mechanism underlying the sign effect.

A leading theory proposes that the sign effect arises from an asymmetry in the anticipated emotional impact of waiting for a negative compared to a positive outcome (Hardisty and Weber, 2009, 2020; Harris, 2012; Loewenstein, 1987; Molouki et al., 2019). When contemplating waiting for a negative outcome, a decision maker may anticipate a sense of *dread*, leading to a negative valuation of the waiting period that counteracts the natural tendency to postpone the unpleasant event. Indeed, individuals sometimes opt to *get it over with,* preferring to endure the negative outcome immediately instead of postponing it (Berns et al., 2006; Harris, 2012; Pezzulo and Rigoli, 2011; Story et al., 2013; Sun et al., 2022). In contrast to the exclusively negative emotion associated with waiting for negative outcomes, the wait for positive outcomes can evoke mixed emotions (Hardisty and Weber, 2009). These include not only the pleasure of anticipating the upcoming reward ("savoring"; Chun et al., 2017; Loewenstein, 1987) but also the displeasure associated with waiting ("impatience"; DeVoe and House, 2012). Emotions associated with the anticipation of positive outcomes may thus have minimal impact on the decision process, leaving largely unaltered the preference for immediate rewards.

Assessing the emotional impact of waiting during intertemporal decisions has been suggested to rely on episodic future thinking (Bulley and Schacter, 2020). Indeed, there is compelling evidence that future thinking plays an important role in the evaluation of choice outcomes by allowing one to pre-experience in the here and now emotions that might play out in the future (Bø et al., 2022; Bulley et al., 2017; Hallford et al., 2020; Miloyan et al., 2019; Schubert et al., 2020). Given the proposition that the sign effect arises from an asymmetry in the valuation of emotions that will be experienced during the wait, Bulley and Schacter (2020) postulated that the sign effect critically depends on episodic future thinking.

The present study evaluated this proposal by assessing the presence of a sign effect in the intertemporal decisions of individuals with hippocampal amnesia, who are severely impaired in their ability to engage in episodic mental simulation (Hassabis et al., 2007; Race et al., 2011). To do so, we administered an intertemporal decision task involving monetary losses and compared findings to those on a similar task involving monetary gains, for which we previously reported intact TD in hippocampal amnesia (Patt et al., 2023; see also Kwan et al., 2012, 2013; Palombo et al., 2015). If the sign effect depends on the episodic simulation of anticipatory emotions during intertemporal decisions, then individuals with hippocampal lesions should fail to show a normal sign effect. That is, whereas we expected neurocognitively healthy individuals to show significantly shallower TD for losses compared to gains, we predicted that this difference would be reduced in the amnesic group.

We additionally aimed to verify that any reduction in the sign effect in individuals with hippocampal amnesia was not due to a group difference in loss aversion, which is the tendency to assign greater value to losses compared to equivalent gains (Baumeister et al., 2001; Camerer, 2005; Kahneman and Tversky, 1979). Extrapolating from the finding that larger gains tend to be discounted less than smaller gains (cf., the "magnitude effect"; Kirby, 1997; Loewenstein and Prelec, 1992; Thaler, 1981), it has been postulated that the sign effect may be attributed to losses inherently carrying larger subjective value than gains (see modeling of discounted utility, al-Nowaihi and Dhami, 2009; Baucells and Bellezza, 2017; Loewenstein and Prelec, 1992). However, this postulate hinges on the idea that losses are subject to the same magnitude effect as gains. Yet, empirical evidence reveals either no effect of magnitude on discounting of losses (Estle et al., 2006; Green et al., 2014; Mitchell and Wilson, 2010) or an opposite effect, with more discounting for larger compared to smaller losses (Hardisty et al., 2013). Therefore, the relationship between loss aversion and the sign effect is disputed, with mounting evidence arguing against such a connection (Hardisty and Weber, 2020; Molouki et al., 2019). Nevertheless, our study included a measure of loss aversion to examine its potential influence on group differences in the sign effect.

1. Method

1.1. Participants

Six individuals with amnesic syndrome secondary to medial temporal lobe pathology (1 female, 5 males) participated in the study. Their average age was 67.7 years (SD = 8.5, range = [58, 80]), average education 15.3 years (SD = 2.9 years, range = [12, 20]), and average verbal IQ 104.7 (SD = 15.4, range = [88, 131]), assessed using the Wechsler Adult Intelligence Scale-III (WAIS-III, Wechsler, 1997a). Etiologies of amnesia included encephalitis (n = 1), stroke (n = 1), hypoxic-ischemic injury secondary to either cardiac or respiratory arrest (n = 3), and status epilepticus followed by left temporal lobectomy (n = 1). Neuropsychological profiles confirmed severe cognitive impairment restricted to the memory domain (see Table 1 for individual demographics and neuropsychological testing summary scores). Available brain imaging of the lesions is presented in Fig. 1 for all individuals in the amnesia group but P4, who had medical contraindications preventing scanning. Medial temporal lobe pathology for P4 was inferred based on etiology (anoxia secondary to cardiac arrest) and neuropsychological profile.

Based on the available scans, the lesion location was restricted to the hippocampus for P3; included the hippocampus as well as the amygdala for P6; included the hippocampus and medial temporal cortices for P1; and extended beyond the medial temporal lobe into the anterolateral temporal neocortex for P2 (due to the temporal lobectomy). For P5, clinical MRI was acquired in the acute phase of herpes simplex encephalitis, yielding no visible T1-weighted findings at that time, but with T2-flair demonstrating bilateral hyperintensities in the hippocampus and MTL cortices as well as in the anterior insula. Across the individuals with amnesia and available brain imaging, the hippocampus was the only area of overlap.

Fourteen healthy control participants (2 females, 12 males) were matched to the amnesia group in age (M = 65.6 years, SD = 9.5, range = [51, 81]), education (M = 15.8 years, SD = 2.9 years, range = [12, 20]), and verbal IQ (M = 109.6, SD = 9.7, range = [93, 123]) assessed using the WAIS-III. All participants provided informed consent in accordance with the Institutional Review Board at the VA Boston Healthcare System.

Our sample size for the amnesia group was limited by the rare occurrence of hippocampal amnesia. A power analysis was implemented with the R package 'pwr' (Champely et al., 2017) for a one-tailed two sample t-test with unequal sample sizes. For an estimate of effect size, we examined previous hippocampal lesion TD studies, including a human lesion study using a classic intertemporal choice task with added episodic demands (Palombo et al., 2015) and animal lesion TD studies where episodic processes have been thought to play a role in the impairment due to the experiential nature of the tasks (Abela and Chudasama, 2013; Bett et al., 2015; Cheung and Cardinal, 2005). Using the Lenhard and Lenhard (2016) F-tests and t-tests to effect size converter, we found approximated Cohen's d effect sizes ranging between 1.0 and 2.1. Assuming a type I error of $\alpha = 0.05$ and power level of $1\text{-}\beta = 0.80$, we found that our study would be capable of detecting effect sizes of Cohen's $d \geq 1.26$ with sample sizes $n_1 = 6$ and $n_2 = 14$ and estimated that our study was generally appropriately powered.

1.2. Paradigms

Two intertemporal choice tasks, one including positive monetary outcomes (TD gain task) and the other including negative monetary outcomes (TD loss task), as well as a loss aversion task were administered. All tasks were programmed and displayed using the Matlab™ Psychtoolbox-3 (Kleiner et al., 2007), and were administered on a Sony VAIO S Series 15.5″ laptop computer with resolution set to 1600 x 900

Table 1
Individual demographics and neuropsychological index scores for participants in the amnesia group.

	Etiology	Age (years)	Education (years)	WAIS III		WMS III		
				VIQ	WMI	GMI	VD	AD
P1	Hypoxic-ischemic	69	12	88	75	52	56	55
P2	Status epilepticus & left temporal lobectomy	56	16	93	94	49	53	52
P3	Hypoxic-ischemic	63	14	106	115	59	72	52
P4	Hypoxic-ischemic	67	17	131	126	86	78	86
P5	Encephalitis	76	13	99	104	49	56	58
P6	Stroke	54	20	111	99	60	65	58

Notes: WAIS-III, Wechsler Adult Intelligence Scale-III (Wechsler, 1997a); VIQ, verbal intelligence quotient; WMI, working memory index; WMS-III, Wechsler Memory Scale-III (Wechsler, 1997b); GM, general memory index; VD, visual delayed index; AD, auditory delayed index.

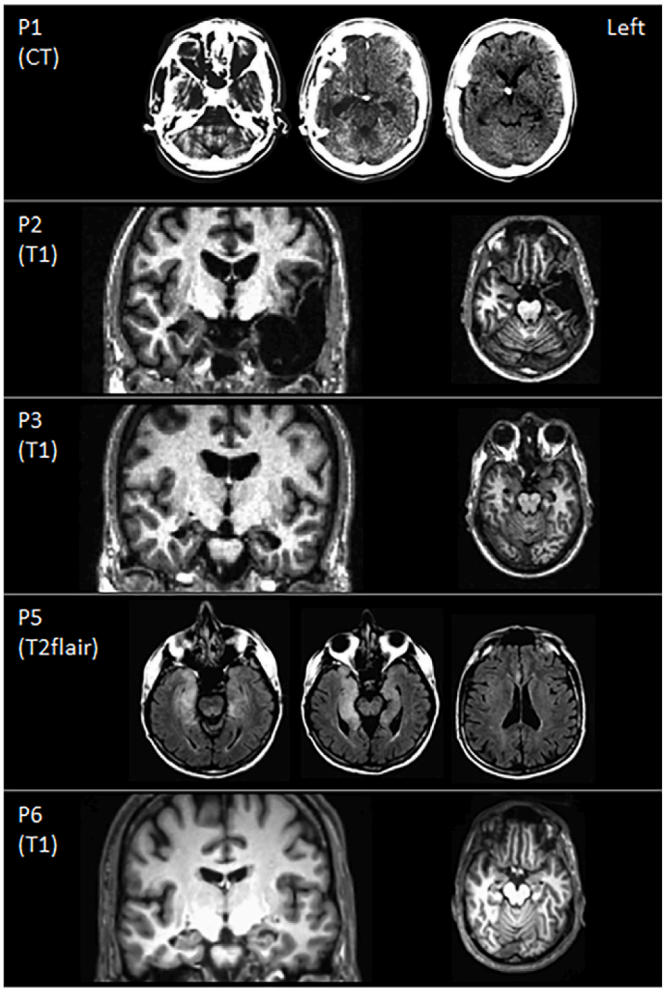

Fig. 1. Brain imaging of the medial temporal lobe (MTL) lesions of the participants in the amnesia group. Available imaging modalities included CT slices in the axial plane for P1, T1-weighted MRI images in the coronal and axial plane for P2, P3, and P6, and T2-Flair MRI images in the axial plane for P5. Imaging could not be collected for P4 due to medical contraindication.

pixels.

Intertemporal Choice Tasks. The TD gain and TD loss tasks consisted of a series of decisions between gaining/losing varying amounts of money immediately or gaining/losing $100 after a delay (Fig. 2). In both tasks, the possible delays were 1 day, 2 days, 1 week, 2 weeks, 1 month, 3 months, 6 months, 1 year, 2 years, and 5 years.[1] In the TD gain task, the possible monetary amounts for the immediate option were: $1, $5, $10, $20, $30, $40, $50, $60, $70, $80, $90, $95, $99, and $100. In the TD loss task, the possible monetary amounts for the immediate option included, in addition to those listed above, values greater than $100, allowing participants the possibility of losing $101, $102, $103, $104, $105, $110, $115, $120, $125, $130, $135, $140, $145, or $150 immediately rather than lose $100 after a delay. These options were added to allow for the possibility that individuals may prefer to lose more money and "get it over with".

At the beginning of each task, detailed instructions were provided as well as a chance to practice with four trials. Each participant was then presented with an individualized series of choices, constructed using a semi-adaptive dichotomy algorithm, allowing efficient determination of indifference points at each preselected delay. An indifference point refers to the amount of money gained or lost immediately that is subjectively equivalent to gaining or losing $100 after a delay. For each preselected delay, the algorithm started with the presentation of an immediate amount randomly chosen in the middle of the monetary interval. On subsequent trials involving that same preselected delay, the amount was adjusted so as to cut in half the current uncertainty interval of the indifference point. For example, for decisions involving a delay of 3 months in the TD loss task, the first decision might involve losing $70 now or losing $100 after a 3-month delay. If the participant chose the immediate option, it implied that the subjective value of losing $100 after a 3-month delay was situated between $70 and $150. The next decision at that delay thus proposed losing $105 now (i.e., the median level amongst the candidate amounts within the uncertainty interval) or $100 after a 3-month delay. The same process was then repeated several times, each time cutting the uncertainty interval in half, until the indifference point converged to one specific amount. Convergence for a preselected delay generally occurred after about 4–5 trials for the TD gain task and after about 6 trials for the TD loss task. In order to limit decision monotony, trials with different delays were interspersed, with random selection of a delay for each new trial among those that had not yet converged to an indifference point. For each task, the semi-adaptive algorithm was run twice, with a short break between the two parts. This strategy permitted collecting two indifference points per delay for each participant. Depending on the speed of convergence of the algorithm, the full task comprised about 90 test trials for the TD gain task and 120 test trials for the TD loss task. The final converged datasets were similar for both tasks, comprising twenty indifference points (two per delay).

Decisions were made by pressing a left or right button on the keyboard. After a choice was made, the selected option was highlighted by a thickening of the frame. A screen with a 0.5 second fixation cross separated a response from the onset of the subsequent trial. The side of the screen on which the immediate (vs. delayed) option was presented was randomized across trials. To verify adequate engagement and understanding of the task, 16 catch trials were also interspersed throughout the task (8 per run of the semi-adaptive algorithm). Half of the catch trials featured choosing between gaining or losing $100 now or gaining or losing a smaller amount of money also now. The other half of the catch trials featured choosing between gaining or losing $100 now or

[1] For participants included in Patt et al. (2023), the TD gain task included an additional delay of 10 years, which was not considered here.

Fig. 2. Illustration of a choice trial during the TD gain and TD loss task. The choices illustrated here with thick light blue frames suggest temporal discounting or impatience in both the gain and loss tasks. Thus, in both cases, the adaptive algorithm will select a monetary amount that is smaller than $80 the next time that an option with a "1 year" delay is presented.

gaining or losing $100 after a delay. This second set of catch trials was used for validity considerations in the TD gain task but not for the TD loss task to account for possible preferences of "getting it over with". Performance was considered valid if the error rate on these trials was less than 25% (4/16 trials in the gain task and 2/8 trials in the loss task).

Loss Aversion Task. A loss aversion task was constructed, modeled after Study 2a of Molouki et al. (2019). In that study, participants were asked if they would accept a gamble involving a 50% chance of receiving $10 and a 50% chance of losing an amount varying between $10 and $0.5. To match the amounts used in our TD tasks, here we increased the amount of the fixed gain option to $100. Further, to limit gambling connotations, choice trials featured the outline of a building with the following instructions: "Inside this building, it is equally likely that you may receive $100 or have to pay $[varying amount]. Would you enter this building?" (see Fig. 3 for an illustration of a choice trial). A semi-adaptive algorithm with dichotomy scheme was employed here also to quickly narrow down (in four to five trials and with a $5 resolution) the amount of loss that would be subjectively equivalent to a $100 gain.

After four practice trials, three adaptive loops were run without break with randomized starting amounts chosen without replacement among $25, $45, and $75. Possible loss amounts ranged between $0 and $150, allowing participants to possibly risk losing more than they could gain. (This occurred in only one participant who was willing to consider losing up to $105). For each participant, the highest value they were willing to lose for a chance of gaining $100 was calculated by averaging the convergence points over the three adaptive loops, and was normalized as a proportion of the possible gain (average convergence point/100). The "loss aversion" index was then calculated as the opposite of that proportion (1-average convergence point/100), so that 0 would indicate null loss aversion (i.e., willingness to risk losing $100 to gain $100), 1 would indicate maximum loss aversion (i.e., unwillingness to risk losing any money to gain $100), and negative values would indicate "risk seeking" behaviors.

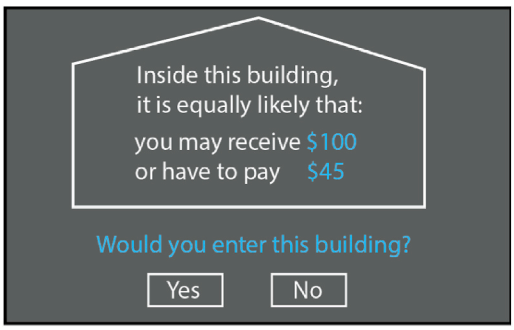

Fig. 3. Illustration of a choice selection screen during the loss aversion task.

1.3. Procedure

Data from the TD gain task from the amnesic participants and 7 of the healthy control participants were included in a separate study that compared temporal discounting in an experiential and in a hypothetical task (Patt et al., 2023). These participants were brought back for the present study to be administered the TD loss task and loss aversion task. The time interval between studies ranged between 10.5 and 29.3 months. The other 7 healthy control participants were administered all three tasks as part of the current study. To avoid the possibility of carry over effects between the TD gain and TD loss tasks, these participants completed the TD tasks in two separate sessions, at least one month apart (2.3 months on average). In the total sample, the average time interval between the TD gain and TD loss tasks was not significantly different across the patient and healthy control groups (Welch two sample *t*-test: $t(17) = 1.08$, $p = .296$). For all participants, the loss aversion task was administered immediately following the TD loss task so that it would not affect intertemporal decisions. The tasks were generally well tolerated and timely completed by the participants.

1.4. Analytical approach

To examine whether the sign effect was present and differed across groups, linear mixed modeling was carried out on the indifference points data obtained from both TD tasks. The model included *Task*, *Group*, and *Group* × *Task* as fixed effects, and *Intercepts* and *Task* as by-subject random effects. Within this modeling framework, the presence of a sign effect was tested by examining the fixed effect of *Task* (with greater indifference points in the TD loss versus TD gain task indicating less discounting for loss compared to gain), and a difference in sign effect magnitude across groups was tested by examining the significance of the *Group* × *Task* interaction. Follow-up linear mixed modeling analyses were carried out to assess the presence of a sign effect in healthy individuals and in individuals with hippocampal lesions separately. The models included *Task* as fixed effect and *Intercepts* and *Task* as random effects. The presence of a sign effect was again tested in the analyses by examining the fixed effect of *Task*. Additional follow-up linear mixed modeling analyses were also carried out on the TD gain and TD loss indifference point data separately to further examine the presence of a group effect at each task level.

We decided not to use computational modeling to compare the gain and loss indifference point curves because previously validated models (e.g., the hyperbolic model of Ainslie (1975), the two-parameter logistic model of Patt et al. (2021)) that have been developed for decisions involving gain cannot readily be applied to fit the temporal discounting of loss (Gonçalves and Silva, 2015). Indeed, models of TD for gain all assume indifference point curves that progressively decrease with increasing delay. However, this may not necessarily be the case for loss, where dread and preferences for "getting it over with" could lead to increasing subjective values of loss with increasing delays. For the same reason, criteria that have been applied previously to identify non-systematic data in gain-related decisions (Johnson and Bickel, 2008) may not apply to loss-related decisions. Thus, we took an empirical approach and assumed that all decision profiles were valid, reflecting the preference of the participant in that moment (see also Gilroy et al., 2022), as long as performance on the catch trials suggested adequate engagement and understanding of the task. An empirical approach has been proposed before with use of the area under the curve (Myerson et al., 2001). Our method of taking into account all the indifference points of each participant simultaneously is roughly analogous to comparing area under the curve across group and task.

To verify that individual differences in loss aversion could not account for the sign effect, sign effect data points were first computed for each delay by subtracting the averaged TD gain indifference points from the averaged TD loss indifference points. These sign effect data points were then modeled using linear mixed modeling analysis, including *Loss Aversion*, *Group*, and the *Loss Aversion* × *Group* interaction as fixed effects, and *Intercepts* as by-subject random effect. We expected to find no significant effect of *Loss Aversion* or *Loss Aversion* × *Group* interaction. As ancillary analyses, to further examine whether loss aversion could have affected TD gain or TD loss separately but in ways that might have canceled out the sign effect, two additional analyses were carried out on the TD gain and TD loss indifference point datasets separately using the same linear mixed model.

For all linear mixed modeling analyses, model fit was computed using maximum likelihood as implemented in the *lme4* package (Bates et al., 2015) of R (R Core Team, 2019). Model fit was compared across models with and without fixed effects of interest using the Akaike's Information Criterion (AIC) (Akaike, 1974) and Bayesian Information Criterion (BIC) (Schwarz, 1978). The significance of differences in model fit vas evaluated using a Likelihood Ratio Test with χ^2-distribution. The significance of fixed effect coefficients was also evaluated within each model with a *t*-test using Satterthwaite's method, implemented using the *R lme4*-package (Bates et al., 2015). Effect sizes for the amount of variance explained by fixed effects were estimated via calculations of R^2 marginal, computed using the method developed by Nakagawa and Schielzeth (2013), implemented with the *piecewiseSEM* R package.

2. Results

2.1. Sign effect

The average indifference point profiles resulting from convergence of the adaptive TD gain and TD loss tasks are presented as a function of delay for every participant in Fig. 4. Sign effect profiles computed as the difference between the loss and gain indifference points are also illustrated in the right panel of Fig. 4.

Results of the linear mixed modeling analyses carried out simultaneously on the indifference point data of the TD gain and TD loss tasks (see Fig. 5) evidenced the presence of a significant sign effect (i.e., a significant effect of *Task*), with indifference points that were greater for loss compared to gain ($\beta = 0.20$, $SE = 0.08$, $t(20.0) = 2.41$, $p = .026$). The sign effect, however, was not different across groups, as evidenced by a *Group* × *Task* interaction that was not significant ($\beta = -0.07$, $SE = 0.10$, $t(20.0) = -0.74$, $p = .466$). The effect of *Group* was also not significant ($\beta = 0.09$, $SE = 0.10$, $t(20.0) = 0.95$, $p = .354$), suggesting similar discounting magnitude across groups. Model fit considerations further confirmed a lack of difference in TD choice behavior across groups: the fit of the model that included *Task*, *Group*, and *Group* × *Task* ($AIC = 167.7$, $BIC = 205.1$, R^2 *marginal* $= 0.065$) was worse across all indicators than the same model without *Group* ($AIC = 164.6$ $BIC = 192.7$, R^2 *marginal* $= 0.055$; model comparison: $\chi^2(2) = 0.9$, $p = 0.638$, ΔR^2 *marginal* $= 0.010$).

In a follow up analysis that considered control participants alone, results confirmed the presence of a sign effect, evidenced by a significant effect of *Task* (loss minus gain: $\beta = 0.13$, $SE = 0.06$, $t(14.0) = 2.2$, $p = 0.045$) and by a significantly better fit ($\chi^2(1) = 4.2$, $p = .041$) of the model with the fixed effect of *Task* ($AIC = 116.0$, $BIC = 142.0$, R^2 *marginal* $= 0.043$) compared to the same model without that fixed effect ($AIC = 118.2$, $BIC = 139.8$).

In individuals with hippocampal lesions, follow up analysis similarly confirmed the presence of a sign effect, also evidenced by a significant effect of *Task* (loss minus gain: $\beta = 0.20$, $SE = 0.07$, $t(6.0) = 2.8$, $p = 0.030$) and by a significantly better fit ($\chi^2(1) = 5.1$, $p = 0.024$) of the model with the fixed effect of *Task* ($AIC = 58.1$, $BIC = 78.9$, R^2 *marginal* $= 0.089$) compared to the model without that fixed effect ($AIC = 61.1$, $BIC = 78.6$).

2.2. Temporal discounting of gains and of losses

Linear mixed modeling analysis of the indifference points data of the TD gain task confirmed the absence of a group effect ($\beta = 0.09$, $SE = 0.10$, $t(20.0) = 0.95$, $p = 0.354$), with fit of the model comprising the fixed effect of *Group* ($AIC = 178.8$, $BIC = 194.8$, R^2 *marginal* $= 0.016$) that was worse ($\chi^2(1) = 0.88$, $p = 0.348$) than that of the model comprising only random intercepts ($AIC = 177.7$, $BIC = 189.7$).

There was also no significant effect of *Group* on the indifference points of the TD loss task ($\beta = 0.02$, $SE = 0.08$, $t(20.0) = 0.26$, $p = 0.801$); and the fit of the model comprising the fixed effect of *Group* ($AIC = -35.0$, $BIC = -19.0$, R^2 *marginal* $= 0.001$) was worse ($\chi^2(1) = 0.07$, $p = 0.799$) than that of the model comprising only random intercepts ($AIC = -36.9$, $BIC = -25.0$).

2.3. loss aversion

The mean loss aversion index was 0.67 ($SD = 0.26$) for participants with hippocampal lesions and 0.38 ($SD = 0.25$) for participants in the control group (Fig. 6). This difference was significant (Welch two sample *t*-test: $t(9.3) = 2.3$, $p = 0.045$) with a large effect size (*Cohen's d* $= 1.1$).

Result of the linear mixed modeling analysis carried out on sign effect datapoints showed no significant effect of *Loss Aversion* ($\beta = -0.06$,

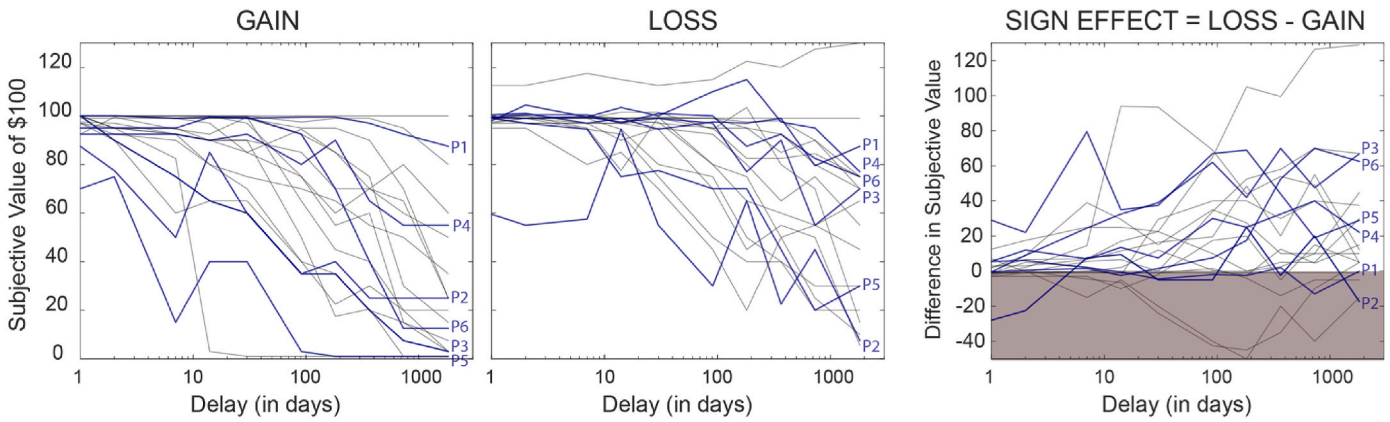

Fig. 4. Individual indifference point curves are presented as a function of delay for the TD gain and TD loss tasks (left and middle panels). Sign effect curves are also presented as a function of delay for each participant (right panel), calculated as the loss minus gain indifference points. The profiles of participants with hippocampal lesions are highlighted in blue.

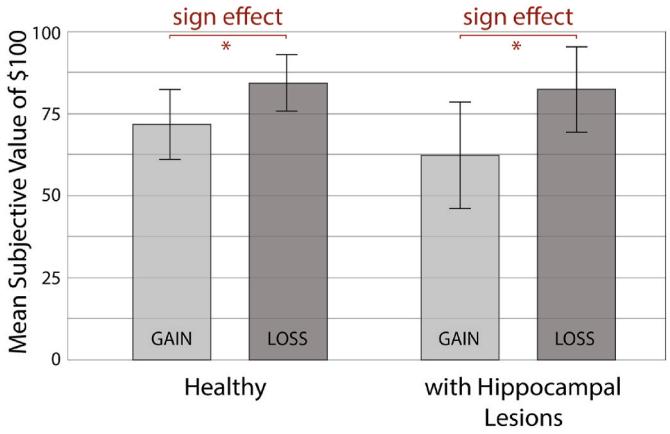

Fig. 5. Marginal means and standard error resulting from the linear mixed modeling analysis, depicting the mean subjective value of $100 averaged across delays in the TD gain versus TD loss task for the healthy participants and participants with hippocampal lesions. A significant sign effect (i.e., a significant effect of Task) was found in both groups (i.e., the subjective value of $100 averaged across delays was greater in the loss compared to gain task) but was not found to differ significantly across groups (no significant effects of Group or Group × Task). Single asterisks indicate significance at level $p < 0.050$.

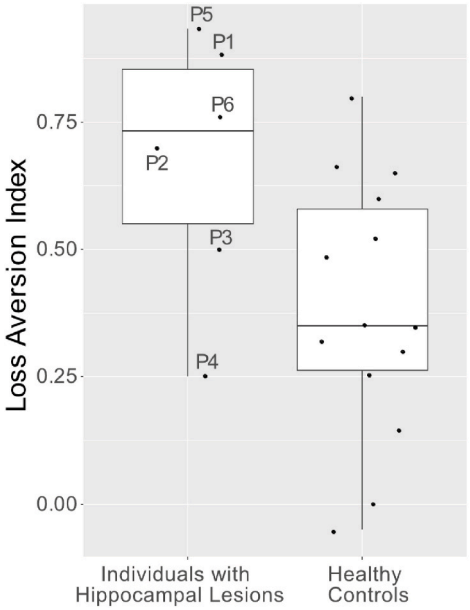

Fig. 6. Boxplot distributions of the loss aversion indices for participants with hippocampal lesions and healthy control participants.

SE = 0.35, *t(20.0)* = −0.17, *p* = 0.868), *Group* (*β* = −0.15, *SE* = 0.27, *t(20.0)* = −0.55, *p* = 0.591), or *Group* × *Loss Aversion* (*β* = 0.15, *SE* = 0.42, *t(20.0)* = 0.35, *p* = 0.727). Further, the fit of the model with these fixed effects (*AIC* = −0.9, *BIC* = 18.9, R^2 *marginal* = 0.019) was no better ($\chi^2(3) = 0.7$, *p* = 0.866) than the model comprising only intercepts (*AIC* = −6.2, *BIC* = 3.7). These results confirm that the sign effect was not associated with loss aversion.

The effect of loss aversion was also examined in separate adjunct analyses on the TD gain and loss indifference points data separately. Numerically, individuals with greater loss aversion tended to display indifference points of decreased magnitude (i.e., more discounting) in both the TD gain task (*β* = −0.29, *SE* = 0.16, *t(20.0)* = −1.8, *p* = 0.084, R^2 *marginal* = 0.052) and TD loss task (*β* = −0.19, *SE* = 0.13, *t(20.0)* = −1.5, *p* = 0.146, R^2 *marginal* = 0.039). The associations however did not reach significance, and the fits of the models that included the fixed effect of *Loss Aversion* (gain: *AIC* = 176.7, *BIC* = 192.6; loss: *AIC* = −37.1, *BIC* = −21.1) did not significantly improve upon the fit of the null model with only intercepts (gain: *AIC* = 177.7, *BIC* = 189.7, $\chi^2(1) = 3.1$, *p* = 0.080; loss: *AIC* = −36.9, *BIC* = −25.0, $\chi^2(1) = 2.2$, *p* = 0.141).

3. Discussion

The present study investigated the role of the hippocampus in the sign effect, the well-established asymmetry in TD of losses versus gains. Despite impairment in episodic simulation (Hassabis et al., 2007; Race et al., 2011), individuals with hippocampal amnesia exhibited an intact sign effect, displaying significantly less discounting for monetary losses compared to monetary gains. Loss aversion, albeit greater in the hippocampal compared to the control group, did not account for the sign effect. These results suggest that hippocampally mediated episodic processes are not necessary for the emergence of a sign effect during intertemporal decisions.

3.1. The sign effect does not require the hippocampus

Compelling evidence suggests that the sign effect is due to the differential impact of anticipatory emotions. Namely, the anticipated dread when waiting for a negative outcome counteracts the tendency to postpone a loss more strongly than the combination of savoring and impatience associated with waiting for a positive outcome enhances the

desire to accelerate a reward (Hardisty and Weber, 2020). Although it has been assumed that these anticipatory emotions depend on episodic simulation (Bulley and Schacter, 2020), the presence of an intact sign effect in patients with hippocampal amnesia suggests that this may not be the case.

A possible alternative mechanism, by which emotions associated with the process of waiting can be factored into decisions, may rely on a semantic consideration of the future. That is, it may be possible to simulate a future emotional state via semantic future thinking, drawing on personal, context-free facts about oneself (Atance and O'Neill, 2005; Szpunar et al., 2014) – for instance, "I usually hate the feeling that something bad is going to happen." Evidence suggests that amnesic patients retain some capacity to engage in semantic future thinking (Klein et al., 2002) albeit not to the same level of detail as healthy controls (Race et al., 2013). This interpretation aligns with the finding that individuals with hippocampal amnesia show a reduction in TD (increased patience) following a semantic generation task consisting of compiling a list of purchasable items (Palombo et al., 2016), even though they do not show the expected effect of episodic future thinking on TD (Palombo et al., 2015). Analogously, we postulate that evaluating the affective toll associated with waiting can rely on semantic future thinking, thus enabling individuals with hippocampal amnesia to display a sign effect similar to that of healthy participants.

The notion that the sign effect does not necessarily rely on hippocampally-mediated processes is supported by the absence of hippocampal activation in brain correlates of the sign effect, highlighting instead important roles for the striatum, medial prefrontal cortex, anterior cingulate cortex, and insula (Pinger et al., 2022; Tanaka et al., 2014; Wang et al., 2023; Y.-Y. Zhang et al., 2016, 2018). Exploiting inter-individual differences in the presence of a sign effect, Tanaka and colleagues explored potential neural correlates of loss magnitude and delay. In those who showed a sign effect, loss magnitude was associated with enhanced neural responses in the insula, and loss delay was associated with enhanced neural responses in the striatum. They interpreted the latter pattern to reflect a neural signature of the dread effect.

3.2. Qualitatively distinct decision patterns in loss discounting

Furrebøe (2020, 2022) has recently argued that it may be too simplistic to interpret the sign effect as simply reflecting quantitative differences in the steepness of discounting, as discounting of losses is associated with qualitatively distinct decision patterns. Indeed, whereas a large portion of individuals display typical discounting profiles, preferring to postpone losses to the future (40%–85% of participants, depending on the study), others display no discounting or even inverse discounting, preferring to deal with losses immediately (Furrebøe, 2020; Gonçalves and Silva, 2015; Myerson et al., 2017; Yeh et al., 2020). Strikingly, most of the no-discounting individuals in the study of Furrebøe (2020) verbalized wanting to get the loss "out of the way". Whether this reflects rule-based responding (e.g., *I always avoid future debt*) or considerations of dread is difficult to ascertain because of ceiling effects in classic TD tasks, which typically prevent the immediate loss from exceeding the delayed loss. Our TD loss task was noteworthy in that it permitted choosing to lose more than $100 in the present rather than waiting and losing $100 in the future, thus enabling measurement of inverse discounting amplitude. Qualitative examination of discounting profiles in our study revealed striking evidence of inverse discounting for negative outcomes in two participants: one healthy participant (N10), who was willing to pay up to $145 now rather than wait and lose $100 in the future, and one participant with hippocampal amnesia (P4) who was willing to pay up to $115 now (see Fig. 4). More subtle inverse discounting was also noted in individual decisions in the TD loss task, with 5 out of 14 healthy participants (36%) and 5 out of 6 participants with hippocampal amnesia (83%) displaying at least one indifference point that converged above $100 by a few dollars. Comparison of frequency between groups was numerically greater in participants with hippocampal amnesia but did not reach significance ($\chi^2(1) = 3.8$, $p = 0.051$). These findings suggest that the choices of amnesic participants, like those of controls, reflect not simply rule based behavior, but rather a nuanced evaluation of how much extra money they are willing to lose now to avoid waiting. These considerations further support the notion that individuals with hippocampal amnesia made decisions that implicated dread in at least a similar (if not greater) degree than was the case for healthy participants. They also support previous proposals that different mathematical models be used for modeling TD of losses and TD of gains (Gonçalves and Silva, 2015).

3.3. Elevated loss aversion in participants with hippocampal amnesia

A secondary objective of the study was to rule out the influence of loss aversion on any observed differences in the sign effect between individuals with hippocampal amnesia and healthy participants. Our results showed no significant differences in the sign effect across groups, although unexpectedly, a markedly higher level of loss aversion was evident in individuals with hippocampal amnesia compared to controls. The lack of significant relation between loss aversion and the sign effect aligns with recent studies suggesting that loss aversion does not provide a viable explanation of the sign effect (Hardisty and Weber, 2020; Molouki et al., 2019). Yet, the higher loss aversion in the hippocampal group deserves further consideration. Although speculative, we entertain several possible reasons for this finding.

First, loss aversion has been linked to emotional arousal, with heightened arousal to losses compared to gains correlating with increased loss aversion (Sokol-Hessner et al., 2009). As such, intrinsic group differences in emotional arousal to negative scenarios could underlie the observed difference in loss aversion. Consistent with this possibility, studies involving decisions regarding moral dilemmas have shown that individuals with hippocampal lesions tend to experience greater emotional arousal, as reflected in self-report measures of emotional intensity (Verfaellie et al., 2021) and physiological skin conductance responses (McCormick et al., 2016). However, the performance of patient P6, whose damage includes the amygdala in addition to the hippocampus, casts doubt on this interpretation. Previous work has suggested that the relationship between loss aversion and arousal responses is mediated by the amygdala (De Martino et al., 2010; Sokol-Hessner et al., 2013). Yet, for this patient who would be expected to have impaired emotional arousal, loss aversion exceeded that of the control participants and was in line with that of the other amnesic participants. It appears unlikely, therefore, that group differences in emotional arousal can account for the heightened loss aversion in the amnesic group.

Another possible reason for the greater loss aversion in the hippocampal group may relate to group differences in risk aversion. Indeed, our measure of loss aversion was intricately linked with willingness to take risks, raising the question of whether group differences in loss aversion might be due to heightened risk aversion in the amnesia group. This is unlikely, given evidence of intact probability discounting in a case study of a patient with hippocampal amnesia (Kwan et al., 2013). Nonetheless, further research comparing loss and risk aversion in hippocampal amnesia would be of interest. This could be achieved, for instance, by employing a decision task that involves both risky and certain options, permitting derivation of separate computational modeling parameters for loss aversion and risk aversion (Klaus et al., 2020).

Finally, it is possible that the greater loss aversion in the amnesia group was due to a methodological feature of the task, which always mentioned the changing loss option after the fixed gain option (e.g., "Inside this building, it is equally likely that you may receive $100 or have to pay $45. Would you enter this building?"). In order to make a decision, participants had to take into account not just the changing loss amount, but also the odds and the gain amount. We speculate that participants with hippocampal lesions, in comparison to controls, may

have placed greater emphasis on the information provided last, given the critical role of the hippocampus in integrating multiple sources of information (Yonelinas, 2013). By this account, the indifference points would be lower in the amnesic patients than in the controls because they did not equally weigh the potential gain and disproportionately focused on the potential loss. This raises the possibility that their loss aversion indifference points might have been higher if the question had been worded differently (i.e., "Inside this building, it is equally likely that you may have to pay $45 or receive $100").

3.4. Limitations

The findings of the current study only apply to hypothetical decisions, and it is unknown whether similar results would be observed with actual monetary incentives. Although temporal discounting for gains has been shown to be relatively consistent regardless of whether the reward is hypothetical or real (Johnson and Bickel, 2002; Madden et al., 2004), recent evidence indicates a slight increase in discounting for losses (more choices of the larger greater loss) when monetary incentives are involved (Yang et al., 2022). These findings suggest an expected reduction in the magnitude of the sign effect in the presence of monetary incentives. Whether such a shift would be similarly observed in individuals with hippocampal lesions is an outstanding question.

It is also unknown whether our findings would generalize to decisions for which outcomes are experienced in the moment. In a previous study using real time delays and consumable rewards, we demonstrated that individuals with hippocampal lesions display TD profiles with flatter slope than do healthy controls, possibly indicating a deficit in computing changes in the experience of the delay (Patt et al., 2023). One might predict hippocampal amnesia to be associated with a similar deficit in intertemporal decisions involving experiential loss. However, we cannot speculate as to the presence of a sign effect in individuals with hippocampal lesions, as no study has examined whether a sign effect characterizes the experiential decisions of healthy individuals.

4. Conclusions and future considerations

In the present study, we demonstrate that individuals with hippocampal amnesia, despite previously documented impairment in episodic future thinking, show a sign effect in temporal discounting comparable to that of control subjects. Importantly, our findings suggest that anticipatory feelings of dread played a role in participants' choices involving negative outcomes. These findings indicate that the sign effect does not require episodic processes and suggest that it may be possible to forecast anticipatory emotions on the basis of semantic future thinking, drawing on non-contextual knowledge about oneself.

Our findings should not be taken to suggest that the sign effect is impervious to the influence of explicit episodic mental simulation. Although episodic foresight might not be a prerequisite for making intertemporal choices, explicit episodic simulation of the future has been shown to lead to flexible and adaptive changes in intertemporal decision-making (Bulley et al., 2016). How episodic simulation may affect the sign effect is challenging to predict given that it will depend on the joint effects of future thinking on intertemporal decisions pertaining to rewards and losses. Although some evidence suggests that the effect of episodic simulation on intertemporal decisions is valence-dependent (Liu et al., 2013; S. Zhang et al., 2018), meta-analyses show that, in general, episodic simulation of future positive or negative events tends to increase patience for delayed rewards (Rösch et al., 2022; Ye et al., 2022). This increase has been proposed to result from enhanced future orientation (Boyer, 2008; Lempert and Phelps, 2016). The impact of episodic simulation on decisions involving negative outcomes is unknown, but one may hypothesize that an enhancement in future orientation would similarly reduce the discounting of losses. Whether such a reduction would occur, and whether it would be greater than the reduction of discounting of gains to produce an increase in sign effect, are questions for future study. Further, considering that the sign effect is thought to reflect the greater anticipated emotional impact of waiting for losses compared to gains, it could be interesting to assess the effect of episodic simulations that specifically draw attention to the waiting period. Pre-experiencing the wait as having an aversive cost (Paglieri, 2013) would presumably produce increased choices of more immediate options in both the gain task (increased discounting) and loss task (decreased discounting), potentially yielding a robust increase in the sign effect. These considerations suggest interesting avenues for future investigations. Further, although our study showed intact intertemporal choices for simple monetary outcomes in individuals with hippocampal amnesia, further research is warranted in this patient group to delineate the boundaries of their preserved decision making abilities and characterize difficulties that may become apparent under conditions that demand greater reliance on episodic future thinking.

CRediT authorship contribution statement

Virginie M. Patt: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Caroline Strang:** Conceptualization, Data curation, Formal analysis, Project administration. **Mieke Verfaellie:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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