**Title:**

# Keeping things in mind for future thinking: Arithmetic booster reduces delay discounting

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## Abstract

People have higher preference for immediate over delayed rewards, and it is suggested that such an impulsive tendency is governed by one's ability to simulate future rewards. Consistent with this view, recent studies have shown that enforcing individuals to focus on episodic future thoughts reduces their impulsivity. Yet, given its multifaceted cognitive processes involved in future thinking, it is not well understood how episodic future thinking functions as an effective tool for modulating individuals' preference for immediate (or delayed) rewards. To examine plausible mechanisms that are linked with future thinking, we used one associative memory task and one working memory task that each of which were administered to manipulate acquired amount of information and individuals' ability to construct a coherent future event, respectively. Comparing with the impacts of three control tasks, we found that individuals' impulsivity was significantly reduced as an effect of arithmetic working memory task, but not of associative memory task. Moreover, this impulsivity reduction was most pronounced in individuals who showed highest working memory training performance. These data provide a mechanistic account of how episodic future thinking affects individuals' subjective valuation of delayed rewards.

## Introduction

In daily decision-making, people sometimes make a choice not because it is better now, but because it will bring them a higher return in the future. One's exaggerated preference for the temporally proximate small reward against the delayed large reward has been referred to as impulsivity[1-4], and the choices that show the opposite pattern—decisions with consideration of future consequences—are considered as outcomes of successful self-control[5-7]. A large body of studies examined the tradeoffs between the time of reward delivery and the amount of reward, and suggested that discounting the value of delayed rewards explains why typical individuals often show seemingly impulsive behaviors, i.e., to choose the small immediate reward over the large delayed reward[8-10]. This framework of temporal discounting in valuation extends to real-life health risk behaviors, such as substance abuse[3,4,11] and problem gambling[12,13]. Consistent with the view that one discounts delayed rewards, individuals who tend to make choices that may deliver immediate pleasure than long-term healthiness (e.g., eating a chocolate bar than an apple as dessert) also showed higher discounting rates in decision-making tasks[14,15].

Why do some individuals discount delayed rewards more than others in valuation process? Recent studies found evidence suggesting that one's ability to simulate future rewards is linked with the extent to which one is sensitive to the temporal delay of rewards[16-19]; individuals' preference for delayed large rewards significantly increased when they were explicitly instructed to imagine the reception of the reward in association with a cue selected from their episodic future plans (e.g., trip to Paris). These findings supported that episodic future thinking induces vivid imagination (simulation) of future reward delivery, and in turn, reduces reward delay discounting. However, the mechanisms via which the induction successfully reduces individuals' delay discounting remains unknown. Here, we focus on two factors that are closely related to future reward simulation and thus may be enhanced in the process of episodic future thinking[17,20,21]: certainty of the simulated contents (amount of information) and individuals' ability to integrate value information across temporal horizon (information accessibility). Specifically, the following two hypotheses were tested. First, additional context information (e.g., specific type of event) associated with the delayed reward will increase certainty of the simulated contents and may help individuals simulate the reward's subjective value. Second, working memory training may increase individuals' performance on simulating (estimating) the reward's subjective value across temporal horizon. These hypotheses were tested by examining whether modulation of each factor indeed significantly reduced individuals' delay discounting, which is an indication of better simulation of delayed rewards. Our results provide evidence that enhancement in one's working memory capacity, but not increased context certainty, is associated with reduction of her delay discounting.

To test the impacts of modulating each factor on reducing individuals' delay discounting, we first administered a classic intertemporal choice task (ITC task; adapted from Kable & Glimcher[22]) (**Fig. 1a, S1a**) and measured individuals' baseline delay discounting. During the ITC task, participants made a series of choices between a fixed immediate reward of 10,000 KRW (around $10) and a larger delayed reward that varied trial to trial (see **Methods** for detailed experimental procedures). Based on participants' choices across three sessions of the ITC task, we estimated individuals' delay discount rate ($k$); we assumed that an objective reward V delivered in a delay of D is subjectively valued following a hyperbolic discount function[8,9,23,24] $SV = V/[1 + kD]$.

After the baseline ITC task, 126 healthy individuals who were recruited for the current study were randomly assigned to one of five types of manipulation tasks: Associative memory task,

Working memory task, and three control tasks. The Associative memory task was design to implicitly provide additional context information about delayed rewards (**Fig. 1b, S1b**), and the Working memory task was to boost individuals' working memory capacity (**Fig. 1c, S1c**). Specifically, by using the Associative memory task manipulation, we examined the possibility that the memorized association would be retrieved during the ITC task due to the use of common cues (i.e., delays for reward delivery vs. delays for planned trips; see **Methods** for details), and that this additional information (i.e., planned trip locations) would provide contexts facilitating the simulation of future rewards[16]. By using the Working memory task, we tested the hypothesis that working memory training would reduce one's delay discounting. This hypothesis was constructed based on previous reports suggesting that mental calculation shares the same cognitive resources with time perception[25], which provides a crucial piece of information in future planning. Moreover, it is known that working memory serves to integrate information across multiple dimensions in mental simulation[20,21]. Thus, we expect that training one's working memory may ease one's future reward simulation.

Three control tasks comprised i) another association task ($\text{Control}_{AM}$) where participants learned association about information irrelevant to delays (**Fig. 1b, S1b**), ii) a spatial attention task ($\text{Control}_{WM}$) where participants were required of using continuous attention, but not working memory (**Fig. 1c, S1c**), and iii) resting (see **Methods** for task details). A second ITC task was administered to all participants after each type of manipulation, and the discount rate changes were calculated to examine the impacts of modulating each factor on reducing individuals' delay discounting. Participants were paid at the end of the study based on the delay and reward of a random single option drawn from all the ITC task decisions the participant made.

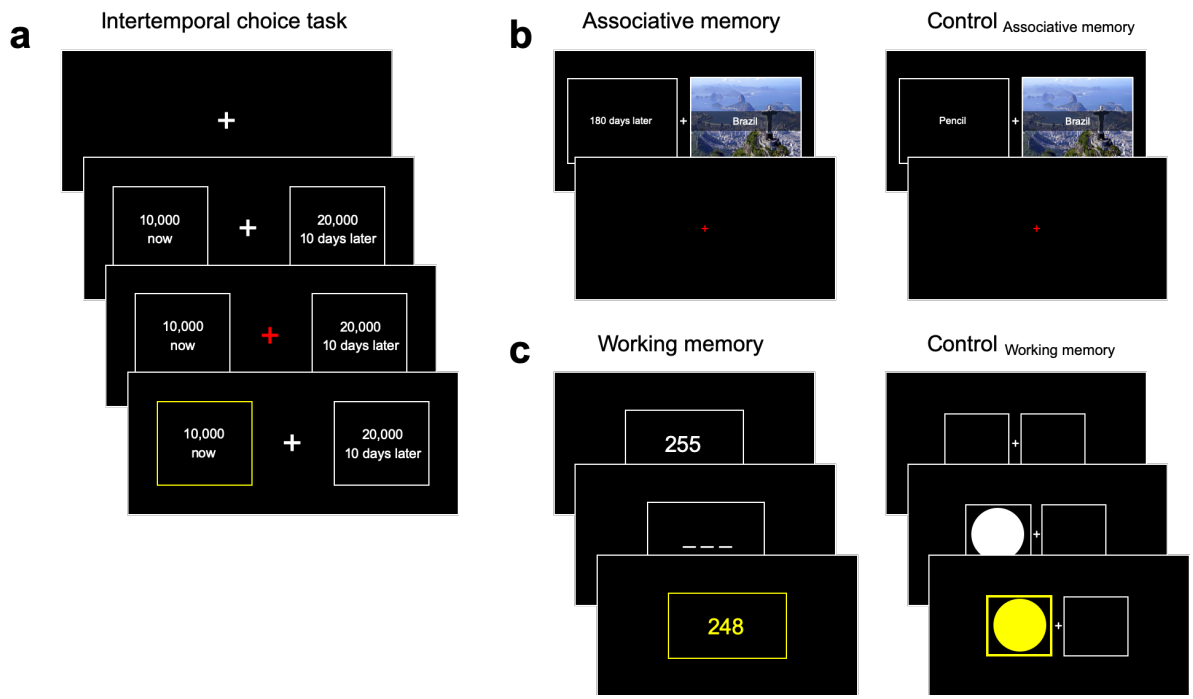


**Figure 1. The intertemporal choice task and cognitive manipulation paradigms. (a)** During the intertemporal choice (ITC) task, participants made choices between an immediate, smaller reward and a delayed, larger reward. The immediate reward was fixed (10,000 Korean Won (KRW)), but the alternative delayed option was constructed using six distinct delays (1,

10, 21, 50, 90, and 180 days) and varying size of delayed rewards (10,300-29,300 KRW) determined by stepwise approach. Individuals could make a response when the crosshair turned red, and a feedback screen followed their choices to highlight the chosen option. **(b, c)** Two manipulation tasks and their control tasks were used to examine impacts of associative and working memory on future reward simulation, and delay discounting in turn. **(b, left)** Associative memory task comprised encoding and retrieval phases (not depicted here). In the encoding phase, participants were asked to memorize associations between the paired stimuli. Specifically, names of the countries with a picture of their representative must-see sights were matched with 'expected preparation time' to go on a trip to the places. Note that the preparation time was presented in the same format as the delays in the ITC task. **(b, right)** $\text{Control}_{\text{AM}}$ was largely identical to the Associative memory task, except that the associations were made between country names and various stationaries. **(c, left)** In Working memory task, participants had to remember a random three digit number presented on the screen (e.g., 255), mentally subtract seven, and report the number on the subsequent screen (e.g., 248). They were asked to repeat this mental calculation (e.g., 241, 234, 237, …) until a new random number was provided. **(c, right)** During $\text{Control}_{\text{WM}}$, participants had to maintain sustained level of attention. Specifically, on each trial, a circle showed up on either left or right half of the screen, and participants were asked to press the arrow key that matches the location as soon as possible.

## Results

All participants (male/female = 71/55, age = 22.00±2.48) completed the first assessment of ITC task to estimate their individual baseline discount rates. At this first assessment, the five sub-groups showed comparable baseline delay discount rates ($\chi^2(4) = 1.20$, $P = 0.88$, Kruskal-Wallis one-way ANOVA). This allowed us to define the impact of each manipulation task as $\Delta\text{Discount rate} = k_{\text{pre-manipulation}} - k_{\text{post-manipulation}}$ where $k$ indicates an individual's estimated discount rate. Larger $k$ refers to more impulsive behavioral choices, and thus a positive ΔDiscount rate indicates a positive manipulation effect on enhancing preference for the delayed reward option (i.e., reducing impulsivity).

As explained above, choices from individuals who were assigned to the Associative memory task and to the Working memory task were used to test the impacts of the content certainty and the working memory capacity on reducing impulsivity, respectively. Neither the Associative memory nor its matched control task ($\text{Control}_{\text{AM}}$) significantly affected individuals' discount rates (Associative memory: Wilcoxon signed rank test, Z = 0.71, signed rank = 162, $P = 0.27$, one-tailed; $\text{Control}_{\text{AM}}$: Z = 1.30, signed rank = 167, $P = 0.097$, one-tailed; **Fig. 2**, **S2a**). On the contrary, individuals who completed the Working memory task showed a significant reduction in their delay discounting (Z = 2.29, signed rank = 182, $P = 0.011$, one-tailed; **Fig. 2, S2a**). Such a training effect did not exist in individuals who participated in a cognitive task that did not require working memory ($\text{Control}_{\text{WM}}$, Z = 0.78, signed rank = 151, $P = 0.22$, one-tailed) or who simply rested in between ITC tasks (Resting, Z = -0.29, signed rank = 118, $P = 0.61$, one-tailed; **Fig. 2, S2a**). These results suggest that individuals' working memory capacity, but not abundancy of context information or individuals' attention level, is linked with their preference for delayed rewards.

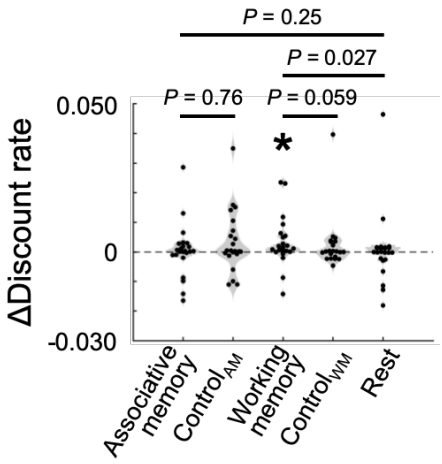


**Figure 2. Working memory training reduces impulsivity.** Each participant group was given with a different type of manipulation task. To examine whether each manipulation had an impact on individuals' impulsivity, we calculated changes in individuals' discount rates by comparing their behavioral patterns during the intertemporal choice (ITC) task conducted before and after the manipulation task: ΔDiscount rate = $k_{\text{pre-manipulation}} - k_{\text{post-manipulation}}$ where $k$ indicates individuals' estimated delay discount rates. Individuals showed significantly reduced discount rates after participating in the Working memory task (Wilcoxon signed rank test, Z = 2.29, signed rank = 182, $P = 0.011$, one-tailed). Furthermore, the mean discount rate change in individuals who participated in the Working memory task was larger compared with that in individuals who rested in between two ITC tasks (Wilcoxon rank sum test, Z = 1.93, rank sum = 591.5, $P = 0.027$, one-tailed) or that in individuals who were assigned to Control$_{WM}$ task (Z = 1.57, rank sum = 549, $P = 0.059$, one-tailed). However, individuals who participated in other manipulation tasks did not show the same pattern (i.e., reduced impulsivity). $^{*}P < 0.05$.

A question that follows is whether or not the current Working memory task indeed functioned as cognitive training. Critically, participants should show enhanced performance across the task. This was indeed the case in our study; 91% of participants showed enhanced performance along the task and across individuals, proportion of correct answers significantly increased along the course of the task (Spearman's correlation, $\rho = 0.66$, $P = 1.34\text{e-}5$; **Fig. 3a**). We further examined whether individuals' working memory task performance matched with the changes in their discount rate. Consistent with our interpretation about the Working memory task as a cognitive training, individuals who had higher mean accuracy in the Working memory task showed larger ΔDiscount rate (reduction of delay discounting after the training) (Spearman's correlation, $\rho = 0.44$, $P = 0.040$; **Fig. 3b**). Moreover, discount rate changes were larger in individuals who showed steeper training slope (Spearman's correlation, $\rho = 0.53$, $P = 0.013$; **Fig. 3c**). When the mean accuracy was measured within each of the five binned task phases, positive relationship between the accuracy and the change in delay discounting remained significant only for the latter half phases (bin 1: Spearman's correlation, $\rho = 0.24$, $P = 0.27$; bin 2: $\rho = 0.37$, $P = 0.21$; bin 3: $\rho = 0.37$, $P = 0.089$; bin 4: $\rho = 0.52$, $P = 0.014$; bin 5: $\rho = 0.55$, $P = 0.0082$; **Fig. 3d**). Note, the fact that the initial task performance (bin 1) was not correlated with the change of delay discounting rate shows that individuals' initial working memory capacity cannot account for their impulsivity change between ITC tasks. All reported analyses showed comparable patterns when we replaced model-based delay discounting rates with model-agnostic measures (i.e., changes in proportion of choosing the delayed option) (**Fig. S3, S4**). These results all together suggest that the Working memory task successfully functions as

cognitive training, and that individuals' training performance rather than their initial working memory capacity predicts the extent to which they discount future rewards less, given the same length of delay.

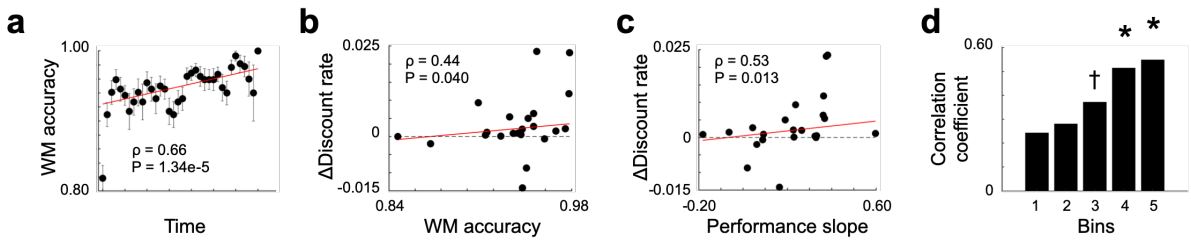


**Figure 3. Individual performance enhancement in working memory training is associated with the level of impulsivity reduction. (a)** Change over time in Working memory task accuracy was measured to examine whether or not individuals showed performance enhancement. Average accuracy within each 10-trial sliding window (with 5-trial overlap) was calculated per participant. Indeed, participants showed a significant performance improvement over time (Spearman's correlation ρ = 0.66, *P* = 1.34e-5). Each dot represents mean accuracy within each window across participants, and error bars indicate s.e.m. **(b)** Individuals' overall performance (i.e., accuracy) in Working memory task was correlated with the changes in their delay discounting rates. Specifically, individuals who had the highest (lowest) accuracy in Working memory showed the largest (smallest) reduction in their estimated impulsivity (positive ΔDiscount rate indicates one's impulsivity reduction). **(c)** Independent of individuals' initial accuracy level, individuals' speed of Working memory performance enhancement (performance slope) was also correlated with the level of impulsivity reduction (ρ = 0.53, *P* = 0.013). Each dot represents an individual, and solid red lines are robust regression lines. **(d)** By dividing the Working memory task into five bins (bin size = 1/3 of the entire task length; sliding window with 1/6 overlap), a stark difference was observed between bins in the association between individuals' Working memory accuracy and their impulsivity reduction levels. Particularly, individuals' Working memory task performance in the later period (3rd to 5th bins) showed strong associations with the extent to which they make less impulsive choices in the post-manipulation ITC task. $^{*}P < 0.05$, $^{\dagger}P = 0.089$.

There was a stark difference in individuals' behavioral pattern during the $\text{Control}_{\text{WM}}$ task (i.e., spatial attention task). Across the task, individuals' task performance (accuracy) gradually decreased (Spearman's correlation, ρ = –0.43, *P* = 6.04e-5; **Fig. S4d**); 66.67% of participants showed decreasing task performance over time. Given this pattern, it is tempting to interpret these results as evidence that participants experienced mental fatigue over an easy and laborious task[26] than being trained for a specific type of executive function (e.g., selective attention). However, alternative explanation is that participants' task performance reflects a ceiling effect due to the low task difficulty, which introduces a potential bias toward finding a decremental effect. Nevertheless, we examined the impact of the task on individuals' impulsivity. Mean task accuracy in the $\text{Control}_{\text{WM}}$ task, but not the slope of task performance change, was positively correlated with the extent to which individuals' delay discounting decreases (Accuracy: ρ = 0.48, *P* = 0.024; Slope: ρ = –0.25, *P* = 0.28; **Fig. S3d, S4e**). Binned task performance confirmed that individuals' mean task accuracy, except for the last phase of the $\text{Control}_{\text{WM}}$ task, explains individual differences in their discounting rate change (bin 1: Spearman's correlation, ρ = 0.52, *P* = 0.015; bin 2: ρ = 0.54, *P* = 0.012; bin 3: ρ = 0.45, *P* =

0.043; bin 4: $\rho = 0.46$, $P = 0.038$; bin 5: $\rho = 0.22$, $P = 0.34$). Together, these results indicate that participating in a continuous attention task does not have an effect of reducing individuals' impulsivity. If any, individuals' average attention level is associated with the extent to which they change their impulsivity at the second examination.

## Discussion

Mental simulation is suggested as one of the four modes of future thinking[27], and broadly defined as cognitive construction of hypothetical scenarios or the reconstruction of real events. As a high-level cognitive function, future thinking is known to be crucial in planning, decision-making, and learning[28-33]. Recent studies showed that such future thinking also plays an important role in evaluating temporally delayed rewards[16,19]. Specifically, individuals preferred delayed rewards more than they used to after being enforced to focus on episodic future thoughts[16]. Given its multifaceted cognitive processes recruited through future thinking, it was premature to conclude why individuals' behavioral preferences changed under the manipulation. The current study focused on two potential factors that determine successful future simulation: contents of the simulation that clarifies what to simulate and one's capacity to simulate that assists one to construct a coherent future event. Without an explicit instruction for future simulation, working memory training, which is known to boost episodic future thinking[21] and chosen herein as one of the training methods for future simulation, successfully reduced participants' delay discounting. On the contrary, providing additional context information through associative memory training did not have a comparable impact on individuals' choice patterns. Furthermore, compared with the impact of the $\text{Control}_{\text{WM}}$ task, it can be inferred that the successful manipulation effect of the Working memory task is not due to its requirement of sustained attention. Our results suggest that working memory training, but not learned context certainty, enhances future reward simulation, and in turn, reduces delay discounting.

Impacts of working memory training for reducing individuals' impulsivity have been inconclusive. For example, delay discounting tendency of individuals who have stimulant use disorder was significantly reduced after multiple sessions of working memory training[34]. In other sample, however, working memory training was effective only for the condition where participants were explicitly cued to execute episodic future thinking[35]. It is worth noting that the former study, but not the latter, included a working memory task that required numerical processing (i.e., digit span). That is, seemingly controversial training effects could be the consequence of subtle differences in working memory task designs. In our study, participants completed a Serial 7s subtraction task[36] as a working memory training, and consistent with previous findings from Bickel et al.[34], individuals' delay discounting rates were significantly reduced. Connecting the dots, it is tempting to speculate that the reason why enforcing individuals' episodic future thinking reduces their delay discounting[35] is because the procedure (thinking about future episodes) triggers individuals to use working memory in simulating future events. However, the current results cannot reject alternative mechanistic possibilities; enhanced working memory may induce individuals to be more apt to simulate future rewards, or even more generally, working memory training may enhance general intelligence[37,38]. Thus, the results should be interpreted with caution.

There have been needs for methods that enhance human's cognitive ability, such that individuals can show faster and more accurate judgements[39,40]. Particularly, reducing individuals' impulsivity has been of interest due to its relevance to health risks[4,11,41,42].

Addressing this, various cognitive training platforms (e.g., Lumosity[43]) and potential intervention frameworks[34,35] were introduced to target multiple cognitive domains, including working memory, problem solving, and fluid reasoning. However, mixed results were reported whether or not the training effects are transferrable to other cognitive functions[44-47]. Our results highlight that there may be different training effects for each specific type of cognitive function. Individuals who completed working memory training showed reduced delay discounting as discussed above, whereas individuals who completed a continuous spatial attention task did not show such a behavioral change. If any, individuals' performance in the spatial attention task ($Control_{WM}$) decreased over time. Such a cognitive 'fatigue' may have a negative impact on other cognitive functions as well[26,48] and thus, the task would not be qualified as a cognitive training program. These results suggest that a cognitive intervention paradigm should be designed with consideration of a potential tradeoff between its positive and negative impacts on a specific target function.

The current study has some limitation that needs further investigation. First, the sample size per manipulation task is small and may lack statistical power (Cohen's d of the working memory training effect = 0.39, which is a small to medium effect). We are planning to transfer the current task designs (intertemporal choice task and other cognitive training paradigms) to an online platform (e.g., Amazon Mechanical Turk) where it is easier to access a diverse and larger number of samples. Second, we assumed that one's working memory capacity should reflect her ability to combine certain information across temporal horizon (to reconstruct or simulate), but we do not have a direct measure proving that participants' ability to simulate indeed changed as a function of their working memory performance. Therefore, one should interpret the causal mechanisms with caution regarding the manipulation to its effect (reduced delay discounting). Third, the null effect of Associative memory task in delay discounting modulation may be due to an insufficient dose of training. This is unlikely, because we did not find any correlation between individuals' memory task performance (accuracy) and change of delay discounting. Still, we cannot completely rule out a possibility that the dose-response for the associative memory training follows a non-linear relationship that has a higher threshold for an effective training result. Further investigation with a longer training period is needed to examine this alternative possibility in the future study. Fourth, the working memory training effect reported here could be a transient change of behavior, and we do not know whether or not the manipulation has sufficient efficiency for a long-lasting intervention.

Nevertheless, the current study delineates two plausible mechanisms explaining the positive relationship between episodic future thinking and changes in delay discounting behavior. Between the two possibilities, we show that a brief working memory training, particularly a task that recruits continuous arithmetic processing, successfully reduces healthy individuals' delay discounting. There are multifaceted implications of these findings. First, our study points out that an individual's tendency to act impulsively may not be a trait-like attribute that does not change, but a feature that can be cultivated differently depending on the situated contexts (e.g., education, and socioeconomic status of the family[49]). Second, given the low task difficulty and the short training time (in the order of minutes rather than days), the arithmetic working memory training may be an appropriate candidate for a 'cognitive prosthesis'[50] that primes individuals to consider consequences from farther temporal horizon. In sum, this work contributes to understanding how episodic future thinking affects individuals' sensitivity to the temporal delay of rewards. More broadly, the current work points to the importance of designing cognitive training paradigms that target more specific cognitive functions for effective and efficient intervention to individuals who have health risk problems, such as obesity[51-53], substance addiction[11,41,54], and pathological gambling[13,55].

## Methods

**Participants.** 126 healthy individuals (male/female = 71/55, age = 22.00±2.48) participated in the current study. All participants provided written informed consent and were paid for their participation. The study was approved by the Institutional Review Boards of Ulsan National Institute of Science and Technology (UNISTIRB-18-18-A). Participants were randomly assigned to one of the five manipulation tasks: two hypothesis-driven tasks—i) association memory task and ii) working memory task—and three control tasks (see **Experimental procedures** for details). 26 students participated in the Associative memory task, and 24 students participated in the Working memory task. For control tasks, comparable number of students were assigned who were age, sex, and education matched (Control for Associative memory task ($Control_{AM}$): N = 25; Control for Working memory task ($Control_{WM}$): N = 24; Resting: N = 26). From the entire participant pool, we excluded six participants from analyses because they expressed superior preference for class credits to monetary incentives, one participant due to her lack of motivation during the task, and eight participants due to no unique solution in parameter estimation. After exclusion, data from 111 participants (male/female = 60/51, age = 22.07±2.54) were used for analyses (see **Table 1** for demographic information for each subgroup).

**Table 1. Demographic data**

| | Associative memory (N = 23) | $Control_{AM}$ (N = 22) | Working memory (N = 22) | $Control_{WM}$ (N = 21) | Resting (N = 23) |
|---|---|---|---|---|---|
| Age (years)[a] | 22.22±2.71 | 21.45±2.15 | 22.32±2.44 | 22.57±2.96 | 21.83±2.46 |
| Male/female[b] | 11/12 | 12/10 | 17/5 | 11/10 | 9/14 |
| Education level[c] | | | | | |
| Some college | 17 | 19 | 19 | 15 | 18 |
| Finished college | 6 | 3 | 3 | 6 | 5 |

Five subgroups were of comparable age[a] ($F(4, 106) = 0.64$, $P = 0.63$), gender[b] ($\chi^2(4) = 5.08$, $P = 0.28$), and education[c] ($\chi^2(4) = 2.55$, $P = 0.64$).

**Experimental procedures.** The aim the current study was to measure individuals' impulsivity, and examine whether manipulation of cognitive factors alter their characteristics. At the beginning of each individual's participation, he or she was randomly assigned to one of the five subgroups, each of which was paired with one type of manipulation task. All participants completed one session of Intertemporal choice task (ITC), one session of the assigned manipulation task, and one additional session of ITC. Participants were paid at the end of the study, based on the delay and reward of a random single option drawn from all the ITC task decisions the participant made. All experiments were performed in accordance with relevant guidelines and regulations.

**Intertemporal choice task.** During the ITC task, participants made a series of choices between a fixed immediate reward of 10,000 KRW (around $10) and a larger delayed reward that varied trial to trial (**Fig. 1a, S1a**). Six distinct delays (1, 10, 21, 50, 90, and 180 days) were used for the delayed reward option, and the value of the option was determined following the staircase

approach. There were two unique initial values for the large delayed reward (15,000 and 20,000 KRW) and the staircase approach is taken for each pair of [delay, initial value]. Specifically, if a participant chose the immediate option at $n^{th}$ step, reward of the delayed option was set to [delayed reward at $n^{th}$ step – 10,000 × $(1/2)^{n-1}$] (n = 1, 2, 3, 4, 5) for the next trial where the same pair of [delay, initial value] was used. On the contrary, if a participant chose the delayed option, reward of the delayed option was set to [delayed reward at $n^{th}$ step + 10,000 × $(1/2)^{n-1}$] for the next trial where the same pair of [delay, initial value] was used. There was one exception. To avoid the delayed reward being equal to or smaller than the immediate reward (10,000 KRW), choices of the delayed option on the trials under the initial value of 15,000 KRW led to the next trial with delayed reward of [delayed reward at $n^{th}$ step – (delayed reward at $n^{th}$ step – 10,000) × $(1/2)^{n-1}$]. This 'titration' procedure repeated for five iterations (steps) for each distinct pair of delay and initial value. Each block comprised 60 trials ([6 delays] × [2 unique initial values for the large reward (15,000 and 20,000 KRW)] × [5 iteration staircase]). To minimize the effect of participants remembering previous pairs of options and their choices, the trial order was randomized for delay × initial value with a unique order per participant. Because of the staircase approach, the subsequent trial was randomly chosen among 12 available pairs [6 delays × 2 initial values] including the pair that was present on the current trial. Again, the amount of delayed reward was determined by the aforementioned rule. Participants completed three blocks of ITC task, 180 trial in total ([6 delays × 2 initial values × 5 steps] × 3 blocks).

**Manipulation tasks.** Previous studies suggested that episodic future thinking induces vivid imagination (simulation) of future reward delivery, and in turn, reduces reward delay discounting[16-19]. To investigate potential mechanisms underlying this induction effect, we examined impacts of two factors that are known to be linked with episodic future thinking (or mental simulation): acquisition of additional context information and enhancement of individual working memory performance. Two manipulation tasks were designed and used to examine these factors, along with three manipulation tasks as controls. In the next section, we explain detailed designs of each manipulation task.

**Manipulation task: Associative memory task.** During Associative memory task, participants were asked to memorize the association between temporal delays and names of the countries, which were introduced as pairs of information about the most wanted places to visit and average duration people spend planning for the trip (**Fig. 1b, S1bi**). This manipulation was to implicitly provide additional information about delayed reward options; if additional context information benefits simulating delayed rewards, the manipulation should decrease individuals' delay discounting in the subsequent ITC task.

Associative memory task comprised two phases: encoding and retrieval phases. Name of 30 different countries and 30 unique temporal delays (preparation time for the trip) were used as pairs. Among the pairs, there were 6 'target' delays that were shared with delays in ITC (1, 10, 21, 50, 90, and 180 days) and 24 'non-target' delays that were never used in ITC. The name of the countries were sorted by their geographical distances from South Korea in ascending order, and they were matched with delays accordingly; examples include [Japan, 1 day], [Vietnam, 10 days], [Taiwan, 21 days], [Philippine, 50 days], [New Zealand, 90 days], and [Brazil, 180 days]. During the encoding phase, there were 60 trials where 30 pairs that should be memorized were presented twice. On each trial, after presentation of the association, participants had to report whether they could successfully remember and vividly image the association between the paired pieces of information.

During the retrieval phase, participants were asked to retrieve previously memorized association pairs and verbally report answers. Specifically, each retrieval trial was cued by one of the 30 delays, and participants' verbal answers of the associated country names were recorded for the accuracy assessment. On each trial, participants used a keypress to notify that they finished providing the answer, and then they reported the extent to which they were confident about the answer in a 5-likert scale (1 = not confident and 5 = very confident). The target delays were tested three times, while the non-target delays were tested only once. In total, there were 42 trials where the target and non-target delay cues were intermixed.

**Manipulation task: Control for Associative memory task ($\mathbf{Control_{AM}}$).** The procedures of the $Control_{AM}$ task were largely identical to those of the Associative memory task (**Fig. 1b, S1bii**). The only difference was that various stationary items were paired with the country names in replacement of delays. Moreover, to match cognitive workload with the Associative memory task, stationary items were used that word length of which names (in Korean) matched the number of digits of the delay it is replacing. We chose stationary items instead of delays, so that no cues during the ITC may trigger retrieval of the information regarding the learned association.

**Manipulation task: Working memory task.** During Working memory task, participants were asked to conduct a series of mental calculation (**Fig. 1c, S1ci**). Specifically, participants played a task so called 'Serial 7s subtraction[36]' where they had to subtract seven from the answer of the previous trial. For example, if the answer of the previous trial was 200, the next answer that should be entered is 193. At the beginning, an initial number was randomly chosen between 107 and 999, and presented on the screen. Participants had to remember the most recently entered answer, so that they could use the information for the subsequent trial. Such needs for reservation of information for a short duration is known to recruit participants' working memory[47]. There were three conditions where the task reset with a new initial number: when participants entered wrong answer, when the answer for the subsequent trial was smaller than 100, or when participants did not enter an answer within 20 seconds. Participants completed two blocks of task where each block lasted for 10 minutes.

**Manipulation task: Control for Working memory task ($\mathbf{Control_{WM}}$).** $Control_{WM}$ task was designed to require continuous attention from participants, but not working memory (**Fig. 1c, S1cii**). On each trial, a circle shaped stimulus showed up on either left or right half of the screen, and participants were instructed to press a left or right arrow key that matches the side of the screen. Stimulus color changed to yellow immediately after a keypress only if the keypress were correct, the color changed to gray when no answers were entered within 1.5 seconds, but no change was made when the submitted answer was incorrect. The next trial started after a short feedback screen (0.5 seconds) and a jittered inter-trial interval (U(0.3, 0.7)). Participants completed two blocks of task where each block lasted for 10 minutes.

**Manipulation task: Resting.** To examine the impacts of manipulation tasks, all participants went through two sessions of ITC tasks, one before and one after the corresponding manipulation. To control for a possibility that the impulsivity change may be induced by the repeated participation in ITC task, we introduced a resting phase for one of the five subgroups. The length of the resting phase was set to 20 minutes, matching the average length of other tasks.

**Behavioral analyses**. For each subgroup, participants' tendency of choosing the delayed option over the immediate option was calculated across three blocks of the ITC task, separately

for the task before and after a manipulation task. As a model-agnostic measure, the impact of each manipulation task was calculated as a difference of the choice ratio between the two choice ratio measures. In addition, we estimated individuals' delay discounting rate ($k$) based on participants' choices across three blocks of the ITC task, separately for the task before and after a manipulation task. We assumed that an objective reward V delivered in a delay of D is subjectively valued following a hyperbolic discount function $SV = V/[1 + kD]$. Individual parameter estimations were conducted with custom MATLAB R2017a scripts using maximum log-likelihood estimation (MLE) at the individual subject level. The *fminsearch* function in MATLAB with different initial values starting estimation was used. After the parameter estimation, changes of delay discounting rates in each subgroup were used as model-based measures of the impact of the manipulation tasks.

To examine whether the extent to which individuals successfully completed their assigned manipulation task was associated with the change of behavioral choice patterns in the ITC task, performance of manipulation tasks were measured accordingly. First, mean accuracies were calculated for each task. Second, for the Working memory task and $Control_{WM}$, temporal evolution in individuals' performance was also examined. To do this, these tasks were binned into equal size (10 trials per bin) using sliding window (5-trial overlap). We examined whether participants showed increasing performance across bins, which would be an indication of successful training of the corresponding cognitive function. Furthermore, to better illustrate the impacts of manipulation tasks on the changes in individuals' impulsivity (i.e., delay discounting rate), we divided each manipulation task in five larger bins (each bin's size was 1/3 of the entire task length where sliding window was used with overlapping 1/6 of task length) and the association within each bin was calculated.

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