HHS Public Access

Author manuscript

Cogn Affect Behav Neurosci. Author manuscript; available in PMC 2020 June 01.

Published in final edited form as:

Cogn Affect Behav Neurosci. 2019 June ; 19(3): 637–652. doi:10.3758/s13415-019-00712-4.

Emotional Content Impacts How Executive Function Ability Relates to Willingness to Wait and Work for Reward

Katherine S. F. Damme[1], **Nicholas J. Kelley**[1], **Meghan E. Quinn**[1,2], **James E. Glazer**[1], **Iris Ka-Yi Chat**[1,3], **Katherine S. Young**[4,5], **Robin Nusslock**[1], **Richard Zinbarg**[1,6], **Susan Bookheimer**[4], and **Michelle G. Craske**[4]

[1]Northwestern University, Institute at Northwestern University

[2]Vanderbilt University, Institute at Northwestern University

[3]Temple University, Institute at Northwestern University

[4]University of California, Los Angeles, Institute at Northwestern University

[5]King's College, London, Institute at Northwestern University

[6]The Family Institute at Northwestern University

Abstract

Research has demonstrated that better value-based decision making (e.g., waiting or working for rewards) relates to greater executive functioning (EF) ability. However, EF is not a static ability but is influenced by the emotional content of the task. As such, EF ability in emotional contexts may have unique associations with value-based decision making where costs and benefits are explicit. Participants (*N*=229) completed an EF task (with both negative and neutral task conditions) and two value-based decision making tasks. Willingness to wait and work were evaluated in separate path models relating the waiting and working conditions and executive function conditions. Willingness to wait and willingness to work showed distinct relationships with executive function ability: greater EF ability on a negative, but not neutral EF task, related to a willingness to wait for a reward; whereas greater EF ability across both EF tasks related to a greater willingness to work for a reward. EF ability on a negative EF task showed an inverted-U relationship to willingness to wait for reward and was most related to willingness to wait at a 6-month delay. Greater EF, regardless of negative or neutral task, was related to a greater willingness to work when reward was uncertain (50%) or likely (88%), but not when reward was unlikely (12%). This study suggests that the emotional content of value-based decisions impacts the relationship between executive function ability and willingness to wait and work for reward.

Corresponding Author: Katherine Damme, Department of Psychology, Northwestern University, 2029 Sheridan Rd., Evanston, IL 60208, Tel: 402-890-3606, Kate.Damme@u.northwestern.edu.

Keywords

executive function; temporal discounting; effort discounting; reward; N-back; EEfRT; DDT

Introduction

The best decision is not always the easiest decision. The best decision can be a particularly difficult choice when that decision requires an individual to wait (Chung & Herrnstein, 1967) or work for a reward (Treadway, Buckholtz, Schwartzman, Lambert & Zald, 2009) because of the cost of time or effort expended. In contrast, easier decisions often do not require waiting or working for a reward. These cost-benefit dilemmas may lead individuals to make decisions that are not in their long-term interest, from how they spend their money to how they spend their time. These value-based decisions can have economic costs for both individuals and society, from retirement (Laibson et al., 1998) to obesity (Wolfe & Colditz, 1998) to academic achievement (Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2017). Therefore, it is critical to understand the cognitive processes underlying value-based decision making.

Value-based decision making refers to decisions where the costs and benefits of options are explicit (Rangel, Camerer & Montague, 2008; Zelazo & Carlson, 2012). During value-based decision making, the costs and benefits of each option are compared to create a subjective value of that option, i.e., value of a reward accounting for the costs of working or waiting (Rangel, Camerer & Montague, 2008). Choices are made based on the subjective value of each option, typically with the goal of maximizing value and minimizing cost. Although research on value-based decision making covers many topics, this paper addresses two common forms of value-based decision making: a willingness to wait for reward and a willingness to work for reward. Despite the general tendency to prefer low effort and immediate rewards, there are substantial individual differences in willingness to wait and work tendencies. Such individual differences are linked to a number of behaviors from drug abuse to depression (Barch, Treadway, & Schoen, 2014; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009; Odum, 2011a).

Willingness to wait for a reward refers to a tendency to forgo smaller immediate rewards for larger future rewards (Odum, 2011a). Individuals generally prefer immediate rewards, and the immediacy of a reward disproportionally impacts decision making (Chung & Herrnstein, 1967). Behaviorally, a higher willingness to wait for reward may lead to better long-term choices, such as greater saving for retirement (Odum, 2011b). Less willingness to wait has been linked to a number of other real-world behaviors, including increased drug abuse, obesity, and gambling (Daugherty & Brase, 2010; Kirby, Winston, & Santiesteban, 2005; Odum, 2011a). Additionally, individual differences in willingness to wait are related to reward sensitivity (Odum, 2011a; Pornpattananangkul & Nusslock, 2016) and impulsivity (Benningfield et al., 2015; Hariri et al., 2006). Biologically, individual differences in willingness to wait choice tendencies are associated with activity in the anterior frontal cortex (Shamosh et al., 2008), amygdala (Churchwell, Morris, Heurtelou & Kesner, 2009), striatum, and posterior insula (Wittman, Leland, & Paulus, 2007). Taken together, past research demonstrates that individual differences in willingness to wait for reward has a variety of real-world implications.

Willingness to work refers to a tendency to expend effort to receive a reward (Botvinick, Huffstetler & McGuire, 2009; Croxson, Walton, O'Reilly, Behrens & Rushworth, 2009). Individuals generally prefer to preserve effort in pursuit of rewards and weigh the subjective value of rewards against the amount of effort that must be expended to access a reward (Botvinick, Huffstetler & McGuire, 2009; Sugiwaka & Okouchi, 2004). Behaviorally, individual differences in willingness to work are related to reward sensitivity (Barch, Treadway & Schoen, 2014; Johnson, Swerdlow, Treadway, Tharp, & Carver, 2017; Treadway et al., 2012) and functional impairment in clinical populations (Barch, Treadway, & Schoen, 2014; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009; Treadway et al., 2012). Biologically, willingness to work for rewards is related to functional activity in the dorsal anterior cingulate cortex, anterior insula, ventral medial prefrontal cortex, and nucleus accumbens, which are all part of the larger value-based decision making network (Aridan et al 2018; Arulpragasam et al, 2018; Botvinick, Huffstetler, & McGuire, 2009; Croxson, Walton, O'Reilly, Behrens, & Rushworth, 2009; Pessiglione et al., 2017). Overall, research on individual differences in willingness to work has provided insight into clinical symptomatology.

Despite both willingness to wait and work being implicated in value-based decision making, there is evidence that these two tendencies are dissociable (Klein-Flügge, Kennerley, Saraiva, Penny, & Bestmann, 2017; Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2017). Behaviorally, willingness to work and wait tendencies are dissociable within an individual, such that someone may be more willing to wait than work or more willing to work than wait (Klein-Flügge, Kennerley, Saraiva, Penny & Bestmann, 2015; Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2017). Additionally, waiting and working for rewards impacts the subjective value of the reward in distinct ways. Waiting for a reward, even at short delays, immediately negatively impacts the value of that reward, whereas working for reward has less impact on the subjective value, but steeply impacts the value of rewards when working for reward becomes tiring (Klein-Flügge, Kennerley, Saraiva, Penny & Bestmann, 2015; Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2017).

Biologically, willingness to wait and work for rewards tendencies are related to distinct but overlapping neural networks. Human neuroimaging studies report that the subjective value of a reward is related to activity in the ventral striatum, pregenual anterior cingulate cortex, and inferior aspects of the frontal cortex for both willingness to wait and work tasks (Prevost et al., 2010; Massar et al., 2015; Seaman et al., 2018). However, decisions regarding whether to work or wait for reward are related to activation in distinct areas (Prevost et al., 2010; Seaman et al., 2018). In direct comparisons of waiting and working for rewards, studies found that choosing to wait for a reward is related to activity in the ventral medial prefrontal cortex (Prevost et al., 2010; Massar et al., 2015; Rudebeck, Walton, Smyth, Bannerman, & Rushworth, 2006; Seaman et al., 2018), whereas choosing to wait for a reward is related to activity in the anterior cingulate cortex (Prevost et al., 2010; Seaman et al., 2018). Additionally, behavioral neuroscience research demonstrated that lesions of the orbitofrontal cortex related to decreased willingness to wait, but not willingness to work, tendencies

(Rudebeck, Walton, Smyth, Bannerman, Rushworth, 2006). In contrast, lesions of the anterior cingulate cortex related to decreased willingness to work, but not willingness to wait (Rudebeck, Walton, Smyth, Bannerman, & Rushworth, 2006). In both studies, individuals demonstrated intact reward valuation, but disruptions to decision making, suggesting specific impairments in executive function ability(Prevost et al., 2010; Massar et al., 2015; Rudebeck, Walton, Smyth, Bannerman, & Rushworth, 2006; Seaman et al., 2018; Klein-Flügge, Kennerley, Saraiva, Penny & Bestmann, 2015; Gatzke-Kopp, Ram, Lydon-Staley, & DuPuis, 2017).

While there are critical differences between willingness to wait and work, both of these tendencies are thought to rely on executive function processes (Bickel, Jarmolowicz, Mueller, Gatchalian & McClure, 2011; Hinson, Jameson, & Whitney, 2003; Olson, Hooper, Collins, & Luciana, 2007; Shamosh & Gray, 2008; Sugiwaka & Okouchi, 2004). Executive function is a broad term for cognitive processes that allow individuals to regulate thoughts and actions in a goal directed manner and adaptively respond to dynamic contexts (Banich, 2009; Friedman & Miyake, 2017; Miyake et al., 2000; Quinn & Joormann, 2015). In contrast to automatic or highly-trained responses, executive function processes allow individuals to flexibly respond to the environment to achieve a goal. Executive function includes three categories of cognitive processes: updating, inhibition and shifting (Miyake et al., 2000). Each of these executive function processes are implicated in decision making (Banich, 2009; Friedman & Miyake, 2017; Rangel, Camerer, & Montague, 2008). During value-based decision making an individual must consider the subjective costs and benefits of each option in working memory (updating), respond to irrelevant information that must be inhibited (inhibition), and switch between mindsets to fully consider each option (shifting). Given the potential role of all three of these executive function processes in value-based decision making (Banich, 2009; Rangel, Camerer, & Montague, 2008) and the high inter-correlation between them (Friedman & Miyake, 2017; Miyake et al., 2000), we will treat these processes as unified executive function ability.

Executive function has another feature that may be critical to value-based decision making. Specifically, executive function ability varies across non-emotional (cold) and emotional (hot) tasks (Zelazo & Carlson, 2012). Cold executive function tasks refer to executive function in affectively neutral or non-emotional contexts; hot executive function tasks refer to executive function in motivationally or emotionally salient contexts (Zelazo & Carlson, 2012). In fact, executive function processes are sensitive to distracting emotional information even when that emotionally salient information is not relevant to the task (Joormann & Vanderlind, 2014; Schmeichel & Tang, 2015; Quinn & Joormann, 2015). Additionally, poorer executive function ability on a hot EF task relates to reduced emotion regulation (Hofmann, Schmeichel, & Baddeley, 2012; Schmeichel & Tang, 2015), increased problem-focused cognitive strategies, (Compton et al., 2011), vulnerability to psychopathology (Joormann & Quinn, 2014), and increased risk-taking behaviors (Patrick, Blair, & Maggs, 2008). As a result, executive function ability on a hot EF task may be particularly important in value-based decision making where emotionally salient costs and rewards are explicit.

Unlike unemotional decisions, value-based decisions inherently contain emotionally salient content, namely the costs of waiting or working and potential rewards. These explicit costs and rewards create a motivational and emotional (hot) context during willingness to wait or work decisions. The emotional context of willingness to wait (Odum, 2011a; Odum, 2011b) and work for reward (Treadway et al., 2012) have led some to theorize that these decisions are better characterized by executive function ability in the face of hot, emotional information as opposed to cold, neutral information (Zelazo & Calrson, 2012). Past research, however, has largely examined the relation of executive function ability on a cold EF task to value-based decision making without considering the role of the emotional context of rewards and costs (Bickel, Jarmolowicz, Mueller, Gatchalian, & McClure, 2011; Hinson, Jameson, & Whitney, 2003; Olson, Hooper, Collins, & Luciana, 2007; Shamosh & Gray, 2008; Sugiwaka & Okouchi, 2004). What remains unknown is if value-based decision making relates more to executive function ability in the face of distracting emotional information (i.e., a hot EF task) or neutral information (i.e., a cold EF task).

The purpose of the present study was to assess how individual differences in executive function ability during both hot and cold EF tasks relate to a willingness to wait and work for rewards. Consistent with past research (e.g., Bickel, Jarmolowicz, Mueller, Gatchalian, & McClure, 2011; Hinson, Jameson, & Whitney, 2003; Olson, Hooper, Collins, & Luciana, 2007; Shamosh & Gray, 2008; Sugiwaka & Okouchi, 2004) we hypothesized that executive function ability on a cold EF task would positively relate to a willingness to work and willingness to wait. In novel analyses, we hypothesized that executive function ability on a hot EF task would also positively relate to a willingness to wait or work. We further predicted that executive functioning on a hot EF task would account for significantly more variance in willingness to wait and work tendencies than executive function ability on a cold EF task, because value-based decisions contain distracting emotional, hot information regarding potential costs and rewards (Zelazo & Carlson, 2012). Finally, we examined relationships between willingness to wait and work task conditions and executive function ability. Within the willingness to wait task there were six delay conditions, and within the willingness to work task there were three different probabilities of receiving a reward: unlikely (12%), uncertain (50%), or likely (88%). We predicted a positive association between EF ability and willingness to wait for rewards that would be stronger for earlier (versus later) rewards. Further, positive associations between EF ability and willingness to work for rewards would be stronger for trials with a high likelihood of being rewarded.

Method

Participants.

Participants in this study were a part of the longitudinal multi-site Brain, Motivation, and Personality Development (BrainMAPD) Project, conducted at University of California-Los Angeles (UCLA) and Northwestern University. Participant recruitment was stratified to include a full range of both reward and threat sensitivity at each site. A total of 282 young adults participated (65% female, age 18-21), 114 of these subjects were recruited from the Los Angeles, CA area and participated at UCLA (65% female, age 18-20) and 168 participants were recruited from the Chicago, IL area and participated at Northwestern

University (66% female, age 18-20). At both sites, participants completed an executive function task (Affective N-Back Task; Quinn & Joormann, 2015) and two value-based decision making tasks in rewarding contexts: Delay Discounting Task (DDT; Johnson & Bickel, 2002; Lagorio & Madden, 2005) and Effort Expenditure for Rewards Task (EEfRT; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009). Across all tasks, a total of 53 participants were excluded based on performance criteria established in the literature for each respective task: five for low accuracy in the N-Back; 27 for DDT performance, which included inconsistent choices; 26 based on EEfRT performance that included not completing enough trials; and five based on poor performance across multiple tasks. For each task the specific exclusion criteria are discussed in detail below. Analyses were conducted on the 229 remaining subjects with acceptable data on all three tasks. Participant data is summarized in Table 1.

Executive Function Task.

N-back tasks measure the accuracy with which subjects update their working memory, a component of executive function (Chatham et al., 2011; Kirchner, 1958; Quinn & Joorman, 2015). In the Affective N-Back task, participants completed 240 trials that consisted of a word presented for 500 ms followed by a blank screen presented for 2,500 ms (Quinn & Joormann, 2015). For each word displayed, participants were instructed to indicate whether each word matched the word that was presented two trials previously, as quickly and accurately as possible. If the currently displayed word matched the word displayed two trials previously, then participants were instructed to press a key labeled “yes”. If the word did not match, then participants were instructed to press a key labeled “no”. This procedure was completed across two conditions (neutral and negative) with 120 trials each. The neutral condition contained only neutral words (e.g, “curtains”), and the negative condition contained both negative (e.g., “failure”) and neutral words (word choice is described in Quinn & Joormann, 2015). These conditions appeared in randomized order of two 60-trial blocks. Our task design is represented in Figure 1a.

Response accuracy was calculated for each of the negative and neutral conditions (Snyder, Myake, Hankin, 2015). Executive function ability in a hot task condition was defined as accuracy during the negative word condition. Executive function ability in a cold task condition was defined as accuracy during the neutral word condition. Errors were defined as multiple responses (i.e. both “yes” and “no” pressed on a single trial), omitted responses, and incorrect responses. Accuracy was used as a basis for exclusion for five participants. Participants with accuracy scores more than 3 standard deviations below the group average accuracy for neutral (M=87%, SD=10%) or negative (M=88%, SD=10%) conditions were considered outliers. It is notable that all of the outlier scores fell below chance performance (50%) in both neutral (M=36%, SD=7%) and negative (M=35%, SD=9%) conditions, which suggests that that poor accuracy was not likely related to condition.

Willingness to Wait in the Delay Discounting Task (DDT).

DDT is a temporal discounting task that assesses willingness to wait for hypothetical rewards (Ahn et al., 2011; Rachlin, Raineri, & Cross, 1991). For each trial, participants made a series of choices between a smaller immediate reward and a future reward of $800 for six delay period conditions that continued for six trials for a total of 36 trials. After their choice was made, a square was presented on the screen reflecting their choice for 1,500 ms, followed by a 3,000 ms fixation. Our task design is represented in Figure 1b. The future choice was set to one of six delay periods: two weeks, one month, two months, six months, one year, three years, or ten years into the future (Ahn et al., 2011; Pompattananangkul & Nusslock, 2016; Rachlin, Raineri, & Cross, 1991). At each delay period, choices began by pitting $400 now against $800 in the future. If the participant chose the immediate reward, then the immediate reward amount on the subsequent trial decreased by half the distance between that amount and $0 (Ahn et al., 2011; Du, Green, & Myerson, 2002). All decisions were for hypothetical rewards and delays, as previous research has found similar response patterns whether the DDT is played for real or hypothetical reward amounts (Johnson & Bickel, 2002; Lagorio & Madden, 2005). For each of the six delay periods, participants completed 6 trials pitting smaller rewards against $800 in the future. On the final trial in each delay period condition (e.g., one month, one year, ten years) the resultant small reward amount was the subjective value of $800 at that given delay period. For example, if a participant always chose the smaller amount during the ten-year condition, then $800 in ten years would have a subjective value equal to receiving $6.25 immediately.

For each participant, the subjective value of $800 at each delay period was fitted into a hyperbolic model, for group average curve see Figure 2D (Pornpattananangkul & Nusslock, 2016). The steepness of the slope within this hyperbolic model (k-value) reflected the preference for smaller-but-immediate (compared to larger-but-delayed) rewards, Figure 2D. DDT-k values were normalized using natural log of k as an index of individual differences in delay discounting tendencies (Shead & Hodgins, 2009). Subjects were excluded based on R^2 value which is calculated based on the hyperbolic curve. A low R^2 suggests that the individual’s decisions on the particular task were highly irregular and cannot be reliably described by the DDT hyperbolic k model. Additionally, irregular or inconsistent choices on the DDT may reflect either a lack of understanding or a lack of attention to the discounting task. A “low” R^2 hyperbolic is defined as R^2 equal to zero or an extreme value (defined by R^2 at 25th percentile – [3* interquartile range]) in this study −.52, which excluded 21 individuals (Shead & Hodgins, 2009). Finally, six individuals were excluded for showing no discounting behavior, as always preferring the larger and later reward, as this value cannot be modeled with a hyperbolic curve. Although it is possible that these individuals always prefer larger later rewards (a potentially relevant endophenotype), it is also possible that the reward value of $800 was not sufficient to detect meaningful behavioral differences in these individuals.

Willingness to Work and Effort Expenditure for Reward Task (EEfRT).

The EEfRT task is an effort discounting task that assessed willingness to work for rewards by pitting small rewards requiring minimal physical effort against larger rewards requiring considerable physical effort. In the EEfRT task, participants were asked to choose between easy and hard trials. There were three probability of reward conditions (88%, 50%, 12%) and each trial had a single probability of reward. For all trials, participants made button presses to reach a goal number of presses. The participant could view their progress toward their goal on the screen. In the easy-task, subjects were required to make 30 button presses, using the dominant hand index finger within 7 seconds, for a potential $1.00 reward. In the hard task, subjects were required to make 100 button presses, using the non-dominant little finger in 21 seconds for a variable reward magnitude ($1.24 - $4.30). For the hard task each level of probability and reward value combination appeared once. All trials were presented in a consistent, randomized order.

In the EEfRT, sixteen participants were excluded for not completing at least 50 trials, which resulted in too few trials in each task condition to properly assess behavior (see Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009 for more details). An additional ten participants were excluded on the basis of the percentage of completed trials, i.e. making enough button presses. Subjects were excluded if they were more than 3 standard deviations below the group mean percentage of completed trials (*M*=95.2%, *SD*=10.8%). Among the individuals that were excluded on this basis, their mean percentage of trials completed was 46.5% (*SD*=16.8%).

Analytic strategy.

Participant demographics and study variables (N-Back Accuracy, DDT-k, and EEfRT percentage of hard choices) were examined for site differences. Follow up analyses did not find any significant impact of site on the size or direction of any effects. All relevant within task conditions were examined to ensure that conditions differed from each other as expected. Specifically, we expected a significant difference in accuracy between N-Back conditions, such that the negative condition would have significantly reduced accuracy. Additionally, we expected that as the length of the delay increases, an individual’s willingness to wait (or the subjective value of that reward) decreases. Finally, we expected that as the probability of reward receipt increases, an individual’s willingness to work, defined as the percentage of hard choices made, increases.

Two separate sets of path analyses compared the relationship between individual differences in executive function ability on hot and cold EF tasks (neutral N-back, negative N-back accuracy) and willingness to wait or work across reward conditions. In each of these path analyses executive function ability on a hot and cold EF task (neutral N-back, negative N-back accuracy) were related to the six delay periods in willingness to wait and three levels of probability in willingness to work (12%, 50%, 88%), respectively. Path analyses were specified to examine the relative fit of competing theoretical models.

In the willingness to wait path analyses, we compared three path models that described the relation between executive function and willingness to wait. This approach allowed us to fully examine all levels of both the N-Back and DDT tasks. The first model constrained the relations among the task conditions to be equal for the six levels of willingness to wait task (two weeks, one month, two months, six months, one year, three years, or ten years) and two levels of the executive function task (negative and neutral), to assess the correlation between willingness to wait and executive function averaged across the different levels of both constructs (see Figure 3A). The second model allowed the relation of executive function with willingness to wait to vary across the six levels of willingness to wait while constraining the associations of the two types of executive function tasks to be equal to each other (see Figure 3B). The third model allowed the relation between willingness to wait conditions and executive function tasks to vary across the two types of executive function tasks while constraining the associations of the six levels of willingness to wait to be equal to each other (see Figure 3C). In the final model, the twelve associations among the six levels of willingness to wait and two types of executive function were all allowed to freely vary (see Figure 3D).

In the willingness to work analyses, we compared three path models that described the relation between executive function and willingness to work. This approach allowed us to fully examine all levels of both the N-Back and EEfRT tasks. The first model constrained the relations among the task conditions to be equal for the three levels of willingness to work (12%, 50%, 88%) and two levels of the executive function task (negative and neutral). The first model assessed the correlation between willingness to work and executive function averaged across the different levels of both constructs (see Figure 4A). The second model allowed the relation of executive function with willingness to work to vary across the three levels of willingness to work while constraining the associations of the two types of executive function tasks to be equal to each other (see Figure 4B). The third model allowed the relation of willingness to work conditions with executive function tasks to vary across the two types of executive function while constraining the associations of the three levels of willingness to work to be equal to each other (see Figure 4C). In the final model, the six associations among the three levels of willingness to work and two types of executive function were all allowed to freely vary (see Figure 4D).

Comparisons among these models provided tests of the main effects of the different levels of willingness to wait or work on executive function tasks and their interaction. If model B fit better than model A, this would indicate that the association between executive function tasks and willingness to wait or work varies as a function of the main effect of the different levels of willingness to wait or work. If model C fit better than model A, this would indicate that the association between executive function and willingness to wait or work varies as a function of the main effect of the different types of executive function tasks (i.e., executive function ability in one of the tasks is a stronger predictor of willingness to work than the other). If model D fit better than model B or C, that would indicate that there is a significant interaction between level of willingness to wait or work and executive function tasks.

Power for the comparisons between correlational models described above was estimated using the conventions and Table 4.3.1 provided in Cohen (1988) for testing the differences between correlations.[1] Accordingly, the current study has power of .30 to detect a small effect size, .96 (q=0.1), to detect a medium effect size (q=0.3), and a 1.0 to detect a large effect size (q=0.5). Alternatively, the sample sizes required to have achieved power of .80 would have been greater than 1000 for a small effect size, 140 for a medium effect size and 52 for a large effect size.

[1]An alternative to our comparisons of the more complex models that allowed paths to differ from each other versus the more constrained models that constrained paths to equal each other would have been to conduct Wald tests on the constraints in a single model. For example, in model C in which the N-back Neutral effect was allowed to differ from the N-back Negative effect, we could have added a Wald test command to test whether these two associations equaled each other. If that test was significant, it would indicated that the two associations are different. That is, it would have indicated the same thing as when model C, which allowed N-back Neutral and N-back Negative to have different effects, provided a significantly better fit than model A, which constrained these two effects to equal each other. Thus, it can be seen that our approach is equivalent to testing the differences between correlations.

Results

Participants.

Group differences in demographic characteristics were examined with independent t-tests and chi-square tests, summarized in Table 1. There was a significant but small site difference in terms of age, UCLA: *M*=19.04, *SD*=0.65; NU: *M*=19.26, *SD*=0.64, *t*(227)=2.53, *p*=.012, *d*=.34. Analyses explored the possible contribution of age to the model, and age showed no significant effect or interaction in any of the models, *p*'s>.28. There was no significant difference in sex across sites, UCLA: 66.2% female; NU: 64.6% female, χ^2(229)=0.90, *p*=.64.

Cross Site Comparison.

Site of data collection had no impact on Affective N-Back Accuracy for either the neutral (UCLA: *M*=89.5%, *SD*=0.08%; NU: *M*=88.8%, *SD*=0.07%, *t*(227)=0.75, *p*=.93) or negative conditions (UCLA: *M*=88.8%; *NU*: *M*=87.4%, *SD*=0.08%, *SD*=0.08%, *t*(227)=1.31, *p*=.35). There was no significant site difference in willingness to wait in terms of DDT hyperbolic-k (UCLA *M*=0.16, *SD*=0.05; NU: *M*=0.23, *SD*=0.22, *t*(227)=1.29, *p*=.20, *d* =.50). There was no significant effect of site on willingness to work as measured by the percentage of hard choice responses (UCLA: *M*=35.4%, *SD*=16.7%; NU: *M*=39.3%, *SD*=14.2%, *t*(227)=1.88, *p*=.07). The potential effect of site on hard choices was also examined by probability of reward conditions (12%, 50%, or 88%). A repeated measures multiple regression demonstrated no significant effect of site, *F*(227,1)=3.45, *p*=.07, nor was there a significant interaction of reward probability across site, *F*(227,l)=1.91, *p*=.15 (see Table 1).

Task Conditions.

There was a very small but significant difference in affective N-Back task performance between negative and neutral conditions, such that neutral word accuracy (*M*=89.1%, *SD*=7.5%) was significantly greater than negative word accuracy (*M*=88.0%, *SD*=7.9%), *t*(227)=2.94, *p*=.004, *d*=0.14 (see Figure 2a). Affective N-Back task accuracies in hot (negative content) and cold (neutral content) conditions were, however, highly positively correlated, *r*(229)=.74, *p*<.001 (see Figure 2b). For the willingness to work task, there was a significant difference in the percentage of hard choices, across the probability of reward conditions: 12%, 50%, and 88%, *F*(2,456)=564.72, *p*<.001, partial η_2=.71. When there was only 12% chance of receiving a reward, participants selected a lower proportion of the harder, more effortful trials (*M*=11.0%, *SD*=1.0%) than when there was a 50% (*M*=41.6%, *SD*=1.6%) or 88% chance of reward (*M*=60.5%, *SD*=1.4%), Figure 2c. The 50% probability of reward condition also had a significantly lower number of hard work choices compared to the 88% chance of reward,*p*<.001. During the willingness to wait task, the subjective value of $800 significantly differed over the six delay periods, *F*(1692,5)=224.00, *p*<.001, partial η^2=.922, all delay periods were significantly different, *p*<.001, see Figure 2d. It should be noted while both DDT and EEfRT reflect cognitive features of reward tendencies (willingness to wait or work for reward), these general tendencies were not significantly correlated, *r*(226)=−.03,*p*=.66.

Executive Functioning and Willingness to Wait by Reward Condition.

To examine the relationships between individual differences in executive function ability on hot and cold EF tasks (Neutral and Negative N-Back accuracy), and the six reward delay conditions in willingness to work task (2 weeks, 1 month, 6 months, 1 year, 3 years, and 10 years), we compared the four path models described above. Model 2 did not provide a significantly better fit than Model 1, $\chi^2(5)=10.31$, $p=.07$. Model 3 provided a significantly better fit than model 1, $\chi^2(1)=5.32$, $p=.02$. Model 4 provided a significantly better fit than Model 3, $\chi^2(10)=23.16$, $p=.01$. Thus, despite Model 3 being accepted as it fit significantly better than Model 1; Model 4 fit significantly better than Model 3. Model 4 was accepted as the model of best fit, Table 2.

Best Fit Model 4 Description.

In Model 4, the ‘one-week delay of reward’ condition did significantly relate to differences in executive function ability in the negative, hot EF task ($\beta=.28$, $p=.003$), but not differences in executive function ability in the neutral, cold EF task ($\beta=-.11$, $p=.25$). The ‘one-month delay of reward’ condition did significantly relate to differences in executive function ability in the negative, hot EF task ($\beta=.35$, $p<001$), but not differences in executive function ability in the neutral, cold EF task ($\beta=-.16$, $p=.08$). The ‘six-month delay of reward’ condition did significantly relate to differences in executive function ability in both the negative, hot EF task ($\beta=.45$, $p<.001$), and in the neutral, cold EF task ($\beta=-27$, $p=.004$). The ‘one-year delay of reward’ condition did significantly relate to differences in executive function ability in the negative, hot EF task ($\beta=.27$, $p=.006$), but not to executive function ability in the neutral, cold EF task ($\beta=-.18$, $p=.06$). The ‘three-year delay of reward’ condition did significantly relate to differences in executive function ability in the negative, hot EF task ($\beta=.28$, $p=.005$), but not to executive function ability in the neutral, cold EF task ($\beta=-.17$, $p=.07$). The ‘ten-year delay of reward’ condition did not significantly relate to differences in executive function ability in the negative, hot EF task ($\beta=.18$, $p=.06$), but was significantly related to executive function ability in the neutral, cold EF task ($\beta=-.21$, $p=.03$), Figure 5A.

Follow-up analyses examined the possibility of a quadratic relationship between executive function ability in the negative, hot EF task across the delay conditions. In this model, 3 factors were created corresponding to the trajectory of DDT performance as a function of the delay interval – an intercept factor that corresponds to the level of DDT performance at the 6-month delay, a linear factor that represents linear changes as a function of the delay interval, and a quadratic factor that represents positive U-shaped or negative inverted U-shaped changes as a function of the delay interval. Then, each factor was regressed on to the differences in executive function ability in the hot EF task (as performance in the neutral context showed a linear increase). The regression of the intercept factor on the differences in executive function ability in the hot EF task was significant ($p<.001$), as was the regression of the quadratic factor on the differences in executive function ability in the hot EF task ($p<.001$), but the linear factor was not significantly related to the differences in executive function ability in the hot EF task ($p=.06$), Figure 5C.

Executive Functioning and Willingness to Work by Reward Condition.

To examine the relationships between individual differences in executive function ability on hot and cold EF tasks (Neutral and Negative N-Back accuracy), and the three levels of probability in willingness to wait (12%, 50%, 88%), we compared the four path models described above. Model 2 provided a significantly better fit than model 1, $\chi^2(2)=21.03$, $p<001$. Model 3 did not provide a significantly better fit than Model 1, $\chi^2(1)=0.33$, $p=.57$. Model 4 did not provide a significantly better fit than Model 2, $\chi^2(3)=1.13$, $p=.77$, Table 2. Thus, Model 2 was accepted as it fit significantly better than Model 1 and was more parsimonious than Model 4, which did not fit significantly better than Model 2. As a result, Model 2 was accepted as the model of best fit, Table 2.

Best Fit Model 2 Description.

In Model 2, the 12% probability of reward condition did not significantly relate to executive function ($\beta=-.07$, $p=.33$), this β-weight refers to path b in Figure 2B. The 50% probability of reward condition significantly related to executive function ($\beta=.40$, $p<.001$), this β-weight refers to path c in Figure 2B. The 88% probability of reward condition significantly related to executive function ($\beta=.29$, $p=.003$), this β-weight refers to path d in Figure 2B. Follow up comparisons of unstandardized coefficients revealed that willingness to work related differently to average executive function accuracy, such that 12% ($\beta=-0.07$, 95% C.I.=−0.19 to 0.05) probability of reward condition was significantly different from the 50% ($\beta=0.40$, 95% C.I.=0.22 to 0.58) or the 88% probability of reward conditions ($\beta=0.13$, 95% C.I.=0.10 to 0.44). The 50% probability of reward and 88% probability of reward condition did not differ in their relationship to executive function, Figure 5D.

Discussion

The present study assessed the relationships between executive function ability on hot and cold EF tasks and willingness to work and willingness to wait for reward. In line with prediction and past research, willingness to wait for rewards positively related to individual differences in executive function ability on a hot EF task. Surprisingly, executive function ability on a cold EF task showed a small, but significant, negative relationship with willingness to wait at a six month and ten-year delay. Finally, the association between executive function ability on a hot EF task and willingness to wait for reward significantly varied across the delay conditions in a quadratic fashion, and the relationship was strongest at a six-month delay. Greater executive functioning ability was positively related to a greater willingness to work, as expected. Contrary to our hypothesis there was no evidence of differential associations between willingness to work and executive function ability by hot and cold EF task condition. In willingness to work analyses, greater executive function ability on both hot and cold EF tasks was related to a greater willingness to work in contexts where the probability of reward was likely (88%) or highly uncertain (50%) compared to when reward was unlikely (12%). This variability by reward condition suggests that executive function ability on both hot and cold EF tasks reflects sensitivity of value-based decisions to contextual features of the reward condition.

Willingness to wait was positively related to executive function ability on a hot EF task as expected, and weakly, but negatively associated with executive function ability on a cold EF task contrary to expectations. The specificity of this relationship suggests that individual differences in executive function abilities on a hot EF task may be a critical aspect of willingness to wait beyond the contribution of executive function ability on a cold EF task. Additionally, this interaction is in line with past research that suggests the emotional and motivational context of willingness to wait decisions may reflect an individual's executive function ability in the face of distracting emotional information (see Zelazo & Carlson, 2012). The amount of variance in willingness to wait explained by executive function ability on a hot EF task varied across the reward delay conditions in a quadratic fashion, peaking at 6 months. Individual differences in executive function ability on a hot EF task were not as predictive of performance at immediate delays compared to other delay conditions (β =.28-35).

This quadratic relationship was in contrast to our prediction that the amount of variance explained by executive function ability on a hot EF task would reflect the general preference for more immediate rewards, i.e. a positive linear relationship. Alternatively, if resisting the temptation of immediate rewards were a direct reflection of executive function ability on a hot EF task, then the relationship of subjective value to executive function ability on a hot EF task would reflect the subjective discounting hyperbolic curve. In contrast to these hypotheses, the unexpected quadratic relationship implies that executive function ability on a hot EF task does not simply reflect a resistance of general tendencies toward immediate reward (consistent with a positive linear relationship) nor the pragmatic discounting of the reward based on delay length (consistent with a hyperbolic relationship). This quadratic relationship also emphasizes that willingness to wait tasks should not be used as a primary metric of executive function ability in a hot context as this would fail to account for the complex contribution of executive function ability in a hot context of different delay conditions. In fact, this quadratic relationship highlights the consideration of other factors that may also influence willingness to wait.

One interpretation of this quadratic relationship may be that executive function ability accounts for the most variance in willingness to wait at a 6 month delay (β =.45) because this is a distant, but imaginable future where it may be beneficial to ignore immediate reward for a future larger reward. In contrast, executive function ability in the face of negative distracting delay information may be less important for very short delays (two weeks, one month) where rewards are more immediate. Executive function ability in the face of negative distracting information may also be less important for very long delays as very few people will be able to overcome the costs of a 1 to 10-year delay in pursuit of a reward. Alternatively, it is also possible that choosing a delayed reward may not always be the best choice. As a result, variance in choosing to wait for a reward may not be accounted for by executive function ability on a hot EF task because it does not reflect the optimal cognitive choice in the face of distracting emotional information. For example, at a very long delay (1 to 10 year delays) where the reward may not be worth the wait at such a long delay. In such a case, choosing to wait for a reward may not be the best choice, and as a result individual differences in a hot EF task are not as predictive for suboptimal choices (β =.18-27). The current finding may contradict the perspective that resisting the temptation of an immediate reward is a direct reflection of executive function ability on a hot EF task. Instead the variability of the relationship between DDT and performance on a hot EF task suggests that delay discounting tasks are not a sufficient primary measure of executive function on a hot EF task, but may reflect the cognitive strategy being employed.

Willingness to work tendencies positively related to executive function ability in general, as expected, but this relationship did not vary significantly across hot and cold EF tasks contrary to our predictions. The amount of variance in willingness to work explained by executive function ability did vary across reward probability conditions. Higher willingness to work for a 50% and 88% chance of reward was positively related to greater executive function ability as expected. However, when there was only a 12% chance of reward, the relationship between individual differences in executive function ability and willingness to work was significantly less positive. The 12% probability of reward condition, where the cost of work is high and chance of reward unlikely, may require less executive function ability. This difference between reward probability conditions also suggests that the low likelihood (12%) trials are not as relevant to individual differences in executive function ability as the uncertain or likely (50% and 88%) trials. This difference between reward probabilities is in line with our prediction that executive function ability would account for more of the variance in individual differences as likelihood of reward increased; although there were no significant differences between the uncertain (50%) or likely (88%) conditions. Finally, the main effect of willingness to wait task conditions suggests that executive function ability in hot EF tasks are particularly important in decisions where there is a reasonable likelihood of reward. In other words, high executive function ability may be useful to sustain performance when the likelihood of reward is high, but when there is a low chance of reward individuals are less motivated to work for the reward regardless of individual differences in executive function ability.

The current study focused on how individual differences in executive function ability on hot and cold tasks relate to value-based decision making. There are, however, additional features of executive function that future studies should consider. First, some research suggests that individual differences in executive function ability on a hot EF task may be impacted differently by positive or negative valence content (Joormann & Vanderlind, 2014). Given that both positively-valenced rewards and negatively-valenced costs are involved in value-based decisions, individual differences in executive function ability in both positive and negative contexts may provide unique contributions to decisions regarding whether to wait or work for rewards. The current study was not equipped to test such a possibility as the executive functioning task contained negative and neutral, but not a positive, executive function task. Nevertheless, future research should examine the potential impact of positive valence.

Future studies should also consider both the unity and diversity of executive function. The current study relied on the N-Back task, which taps a general factor of executive function rather than any one specific facet (Jaeggi, Buschkuehl, Perrig & Meier, 2010; Miller, Price, Okun, Montijo & Bowers, 2009). As a result, the current study is unable to speak to the relative contributions of specific facets of executive function to value-based decision making. However, there are a number of facets of executive function that may be important for future research on willingness to work and wait. Specifically, Miyake and colleagues (2000) highlighted the importance of both a general factor and specific facets (i.e., shifting, updating, inhibition) to executive functioning. While distinguishable processes underlying executive function are highly interrelated, they may provide a distinct contribution to willingness to wait and willingness to work tendencies. For example, inhibition blocks out irrelevant information during value-based decision making, and thus deficits in inhibition may lead to impulsive decisions (e.g., less willingness to wait). Similarly, updating abilities may help individuals properly weigh the subjective value of options based on the changing costs and benefits, and deficits in updating could result in less willingness to wait or work for rewards. Finally, shifting is the ability to move swiftly between multiple actions, and greater shifting abilities may better equip individuals to consider the multiple outcomes of any given value-based decision making. Future studies should examine the extent to which each facet of executive function ability relates to value-based decision making (Miyake et al., 2000).

The distinct relationship of willingness to wait and work choice tendencies to executive function ability may reflect the differences in the neural substrates underlying these decisions. The current study found that willingness to wait choice tendencies are related to executive function ability in the face of negative information. From past research we know that willingness to wait choice is particularly related to activity in the ventral medial prefrontal cortex (Prevost et al., 2010; Massar et al., 2015; Rudebeck, Walton, Smyth, Bannerman, & Rushworth, 2006; Seaman et al., 2018). This ventral medial prefrontal cortex activity during willingness to wait choices may also be related to executive function ability in the face of distracting, emotional stimuli. In contrast, the current study found that willingness to work choices are related to executive function ability, regardless of whether it is a hot or cold EF task. Past research has also demonstrated that willingness to work is related to anterior cingulate cortex activity (Rudebeck, Walton, Smyth, Bannerman, & Rushworth, 2006; Prevost et al., 2010; Seaman et al., 2018). It is possible that the anterior cingulate cortex activity during willingness to work choices may also be related to the overall executive function ability. Unfortunately, one limitation of this behavioral study is that it is not able to directly examine relationship of activity in these regions to individual differences in executive function in emotional contexts. Future studies should examine the neural mechanisms underlying associations between executive function and value-based decision making observed in the current study.

Another potential limitation is that there may be relevant differences in the value-based decision making tasks. Particularly, the willingness to wait task asked participants about hypothetical monetary rewards at hypothetical delays. In contrast, the willingness to work task asked participants to expend real effort for real monetary rewards. Some research suggests that hypothetical rewards are less salient than real monetary rewards, and that this difference results in distinct effects on value-based decision making behavior and related brain activity (Xu et al., 2018). As a result, one might expect that the willingness to wait task would be unrelated to executive function ability on hot EF task because the hypothetical rewards and costs would be less emotional and distracting. Similarly, if the willingness to wait task was not sufficiently salient, then we might expect that it would reflect executive function ability on a cold EF task, as the task contained neutral, hypothetical information.

Our findings, however, are inconsistent with this concern. In fact, we found that willingness to wait for reward was more related to executive function ability on a hot EF task than a cold EF task. It is also noteworthy that previous research has also observed that real and hypothetical rewards do not differentially impact delay discounting tendencies (Johnson & Bickel, 2002; Lagorio & Madden, 2005). It is still possible that the use of hypothetical rewards underestimated the impact of individual differences in executive function ability on hot EF tasks on willingness to work in the current study. Therefore, future studies should explore how individual differences in executive function ability in the face of distracting emotional or neutral information relate to both value-based decision making for real and hypothetical costs and rewards.

In conclusion, our results suggest that a willingness to wait and a willingness to work relate to executive functioning tendencies. Greater executive function ability on a hot EF task related to a greater willingness to wait more so than did executive function ability on a cold EF task. In contrast, better executive function ability on both hot and cold EF tasks related to a greater willingness to work with no evidence of differential associations between individual differences in executive functioning ability based on whether it was a hot or cold EF task. We also found that the strength of the relationship between individual differences in executive function ability varied across value-based decision conditions. A greater willingness to wait for reward related to executive function ability on a hot EF task more strongly when the reward was in 6 months compared to the more immediate (1-week, 1 month) or distant delays (1 year, 3 years, 10 years). Similarly, we found that a greater willingness to work for reward related to executive functioning when reward was uncertain (50%) or likely (88%) compared to when the reward was unlikely (12%). These results both emphasize the importance of individual differences in executive function ability during value-based decision making, and provide evidence that the importance of executive function ability may vary along cost and benefit features of the decision. Collectively, our results suggest that individual differences in executive function ability on hot tasks may be particularly important for willingness to wait, but that executive function ability in general is important for willingness to work. Therefore, improved executive function ability in the face of distracting emotional information may be of particular benefit in willingness to wait decisions such as increasing saving for retirement (Odum, 2011a) or reducing problematic behaviors such as drug abuse, obesity, and gambling (Daugherty & Brase, 2010; Kirby, Winston & Santiesteban, 2005; Odum, 2011a). In contrast, strategies to improve executive function in general may benefit willingness to work decisions relevant to clinical disorders such as depression and schizophrenia (Barch, Treadway & Schoen, 2014; Treadway, Buckholtz, Schwartzman, Lambert, & Zald, 2009).

Data for the experiments reported here is available upon request through the BrainMAPD Project website, the experiment was not preregistered, and all R and MPLUS analyses scripts are available at github.com/katedamme.

References

Ahn WY, Rass O, Fridberg DJ, Bishara AJ, Forsyth JK, Breier A, … & O'donnell BF (2011). Temporal discounting of rewards in patients with bipolar disorder and schizophrenia. Journal of Abnormal Psychology, 120(4), 911. [PubMed: 21875166]

Aridan N, Malecek NJ, Poldrack RA, & Schonberg T (2018). Neural correlates of effort-based valuation with prospective choices. NeuroImage.

Arulpragasam AR, Cooper JA, Nuutinen MR, & Treadway MT (2018). Corticoinsular circuits encode subjective value expectation and violation for effortful goal-directed behavior. Proceedings of the National Academy of Sciences, 115(22), E5233–E5242.

Balleine BW (2005). Neural bases of food-seeking: affect, arousal and reward in corticostriatolimbic circuits. Physiology & Behavior, 86(5), 717–730. [PubMed: 16257019]

Banich MT (2009). Executive function: The search for an integrated account. Current Directions in Psychological Science, 18(2), 89–94.

Barch DM, Treadway MT, & Schoen N (2014). Effort, anhedonia, and function in schizophrenia: Reduced effort allocation predicts amotivation and functional impairment. Journal of Abnormal Psychology, 123(2), 387. [PubMed: 24886012]

Bickel WK, Jarmolowicz DP, Mueller ET, Gatchalian KM, & McClure SM (2012). Are executive function and impulsivity antipodes? A conceptual reconstruction with special reference to addiction. Psychopharmacology, 221(3), 361–387. [PubMed: 22441659]

Benningfield MM, Blackford JU, Ellsworth ME, Samanez-Larkin GR, Martin PR, Cowan RL, & Zald DH (2014). Caudate responses to reward anticipation associated with delay discounting behavior in healthy youth. Developmental Cognitive Neuroscience, 7, 43–52. [PubMed: 24309299]

Berkman ET, Hutcherson CA, Livingston JL, Kahn LE, & Inzlicht M (2017). Self-control as value-based choice. Current Directions in Psychological Science, 26(5), 422–428. [PubMed: 29335665]

Botvinick MM, Huffstetler S, & McGuire JT (2009). Effort discounting in human nucleus accumbens. Cognitive, Affective, & Behavioral Neuroscience, 9(1), 16–27.

Carver CS, & White TL (1994). Behavioral inhibition, behavioral activation, and affective responses to impending reward and punishment: The BIS/BAS scales. Journal of Personality and Social Psychology, 67, 319–333.

Chatham CH, Herd SA, Brant AM, Hazy TE, Miyake A, O'Reilly R, Friedman NP, (2011). From an executive network to executive control: A computational model of the n-back task. Journal of Cognitive Neuroscience, 23(11), 3598–3619. [PubMed: 21563882]

Chung SH, & Herrnstein RJ (1967). Choice and delay of reinforcement. Journal of the Experimental Analysis of Behavior, 10(1), 67–74. [PubMed: 16811307]

Churchwell JC, Morris AM, Heurtelou NM, & Kesner RP (2009). Interactions between the prefrontal cortex and amygdala during delay discounting and reversal. Behavioral Neuroscience, 123(6), 1185. [PubMed: 20001103]

Cohen J (1988). Statistical power analyses for the behavioral sciences. 2nd ed. New York:Lawrence Erlbaum Associates, Publishers.

Compton RJ, Arnstein D, Freedman G, Dainer-Best J, Liss A, & Robinson MD (2011). Neural and behavioral measures of error-related cognitive control predict daily coping with stress. Emotion, 11(2), 379. [PubMed: 21500906]

Croxson PL, Walton ME, O'Reilly JX, Behrens TE, & Rushworth MF (2009). Effort-based cost–benefit valuation and the human brain. Journal of Neuroscience, 29(14), 4531–4541. [PubMed: 19357278]

Daugherty JR, & Brase GL (2010). Taking time to be healthy: Predicting health behaviors with delay discounting and time perspective. Personality and Individual Differences, 48(2), 202–207.

Day JJ, Jones JL, Wightman RM, & Carelli RM (2010). Phasic nucleus accumbens dopamine release encodes effort-and delay-related costs. Biological Psychiatry, 68(3), 306–309. [PubMed: 20452572]

Denk F, Walton ME, Jennings KA, Sharp T, Rushworth MFS, & Bannerman DM (2005). Differential involvement of serotonin and dopamine systems in cost-benefit decisions about delay or effort. Psychopharmacology, 179(3), 587–596. [PubMed: 15864561]

Du W, Green L, & Myerson J (2002). Cross-cultural comparisons of discounting delayed and probabilistic rewards. The Psychological Record, 52(4), 479–492.

Friedman NP, & Miyake A (2017). Unity and diversity of executive functions: Individual differences as a window on cognitive structure. Cortex, 86, 186–204. [PubMed: 27251123]

Gatzke-Kopp LM, Ram N, Lydon-Staley DM, & DuPuis D (2018). Children's sensitivity to cost and reward in decision making across distinct domains of probability, effort, and delay. Journal of behavioral decision making, 31(1), 12–24. [PubMed: 29353962]

Hariri AR, Brown SM, Williamson DE, Flory JD, de Wit H, & Manuck SB (2006). Preference for immediate over delayed rewards is associated with magnitude of ventral striatal activity. Journal of Neuroscience, 26(51), 13213–13217. [PubMed: 17182771]

Hinson JM, Jameson TL, & Whitney P (2003). Impulsive decision making and working memory. Journal of Experimental Psychology: Learning, Memory, and Cognition, 29(2), 298–306.

Hofmann W, Schmeichel BJ, & Baddeley AD (2012). Executive functions and self-regulation. Trends in Cognitive Sciences, 16(3), 174–180. [PubMed: 22336729]

Jaeggi SM, Buschkuehl M, Perrig WJ, & Meier B (2010). The concurrent validity of the N-back task as a working memory measure. Memory, 18(4), 394–412. [PubMed: 20408039]

Johnson MW, & Bickel WK (2002). Within-subject comparison of real and hypothetical money rewards in delay discounting. Journal of the experimental analysis of behavior, 77(2), 129–146. [PubMed: 11936247]

Johnson SL, Swerdlow BA, Treadway M, Tharp JA, & Carver CS (2017). Willingness to Expend Effort Toward Reward and Extreme Ambitions in Bipolar I Disorder. Clinical Psychological Science, 5(6), 943–951.

Joormann J, & Quinn ME (2014). Cognitive processes and emotion regulation in depression. Depression and anxiety, 31(4), 308–315. [PubMed: 24668779]

Joormann J, & Vanderlind WM (2014). Emotion regulation in depression: The role of biased cognition and reduced cognitive control. Clinical Psychological Science, 2(4), 402–421.

Klein-Flügge MC, Kennerley SW, Saraiva AC, Penny WD, & Bestmann S (2015). Behavioral modeling of human choices reveals dissociable effects of physical effort and temporal delay on reward devaluation. PLoS computational biology, 11(3), e1004116. [PubMed: 25816114]

Kirby KN, Winston GC, & Santiesteban M (2005). Impatience and grades: Delay-discount rates correlate negatively with college GPA. Learning and Individual Differences, 15(3), 213–222.

Lagorio CH, & Madden GJ (2005). Delay discounting of real and hypothetical rewards III: Steady-state assessments, forced-choice trials, and all real rewards. Behavioural processes, 69(2), 173–187. [PubMed: 15845306]

Laibson DI, Repetto A, Tobacman J, Hall RE, Gale WG, & Akerlof GA (1998). Self-control and saving for retirement. Brookings papers on economic activity, 1998(1), 91–196.

Massar SA, Libedinsky C, Weiyan C, Huettel SA, & Chee MW (2015). Separate and overlapping brain areas encode subjective value during delay and effort discounting. Neuroimage, 120, 104–113. [PubMed: 26163803]

Mazur JE (1987). An adjusting procedure for studying delayed reinforcement in: Commons ML, Mazur JE, Nevins JA & Rachlin H (Ed.s) *Quantitative Analysis of Behavior*, vol. 5, *The effect of delay and of intervening events on reinforcement value*, pp. 55–73 (Hillsdale, NJ, Erlbaum).

Miller KM, Price CC, Okun MS, Montijo H, & Bowers D (2009). Is the n-back task a valid neuropsychological measure for assessing working memory? Archives of Clinical Neuropsychology, 24(7), 711–717. [PubMed: 19767297]

Miyake A, Friedman NP, Emerson MJ, Witzki AH, Howerter A, & Wager TD (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. Cognitive Psychology, 41(1), 49–100. [PubMed: 10945922]

Odum AL (2011). Delay discounting: I'm ak, you're ak. Journal of the Experimental Analysis of Behavior, 96(3), 427–439. [PubMed: 22084499]

Odum AL (2011). Delay discounting: trait variable? Behavioural Processes, 87(1), 1–9. [PubMed: 21385637]

Olson EA, Hooper CJ, Collins P, & Luciana M (2007). Adolescents' performance on delay and probability discounting tasks: contributions of age, intelligence, executive functioning, and self-reported externalizing behavior. Personality and Individual Differences, 43(7), 1886–1897. [PubMed: 18978926]

Patrick ME, Blair C, & Maggs JL (2008). Executive function, approach sensitivity, and emotional decision making as influences on risk behaviors in young adults. Journal of Clinical and Experimental Neuropsychology, 30(4), 449–462. [PubMed: 18938681]

Pessiglione M, Vinckier F, Bouret S, Daunizeau J, & Le Bouc R (2017). Why not try harder? Computational approach to motivation deficits in neuro-psychiatric diseases. Brain, 141(3), 629–650.

Pfeifer JH, & Berkman ET (2018). The Development of Self and Identity in Adolescence: Neural Evidence and Implications for a Value-Based Choice Perspective on Motivated Behavior. Child Development Perspectives.

Pornpattananangkul N, & Nusslock R (2016). Willing to wait: elevated reward-processing EEG activity associated with a greater preference for larger-but-delayed rewards. Neuropsychologia, 91, 141–162. [PubMed: 27477630]

Prévost C, Pessiglione M, Météreau E, Cléry-Melin ML, & Dreher JC (2010). Separate valuation subsystems for delay and effort decision costs. Journal of Neuroscience, 30(42), 14080–14090. [PubMed: 20962229]

Quinn ME, & Joormann J (2015). Stress-induced changes in executive control are associated with depression symptoms: Examining the role of rumination. Clinical Psychological Science, 3(4), 628–636.

Rachlin H, Raineri A, & Cross D (1991). Subjective probability and delay. Journal of the Experimental Analysis of Behavior, 55(2), 233–244. [PubMed: 2037827]

Rangel A, Camerer C, & Montague PR (2008). A framework for studying the neurobiology of value-based decision making. Nature Reviews Neuroscience, 9(7), 545. [PubMed: 18545266]

Rudebeck PH, Walton ME, Smyth AN, Bannerman DM, & Rushworth MF (2006) Separate neural pathways process different decision costs. Nature Neuroscience, 9(9), 1161. [PubMed: 16921368]

Schmeichel BJ, & Tang D (2015). Individual differences in executive functioning and their relationship to emotional processes and responses. Current Directions in Psychological Science, 24(2), 93–98.

Seaman KL, Brooks N, Karrer TM, Castrellon JJ, Perkins SF, Dang LC, & Samanez-Larkin GR (2018). Subjective value representations during effort, probability and time discounting across adulthood. Social cognitive and affective neuroscience, 13(5), 449–459. [PubMed: 29618082]

Shamosh NA, DeYoung CG, Green AE, Reis DL, Johnson MR, Conway AR, … & Gray, J. R. (2008). Individual differences in delay discounting: relation to intelligence, working memory, and anterior prefrontal cortex. Psychological science, 19(9), 904–911. [PubMed: 18947356]

Shamosh NA, & Gray JR (2008). Delay discounting and intelligence: A meta-analysis. Intelligence, 36(4), 289–305.

Shead NW, & Hodgins DC (2009). Probability discounting of gains and losses: Implications for risk attitudes and impulsivity. Journal of the Experimental Analysis of Behavior, 92(1), 1–16. [PubMed: 20119519]

Snyder HR, Miyake A, & Hankin BL (2015). Advancing understanding of executive function impairments and psychopathology: bridging the gap between clinical and cognitive approaches. Frontiers in psychology, 6, 328. [PubMed: 25859234]

Sugiwaka H, & Okouchi H (2004). Reformative self-control and discounting of reward value by delay or effort. Japanese Psychological Research, 46I(1), 1–9.

Treadway MT, Buckholtz JW, Schwartzman AN, Lambert WE, & Zald DH (2009). Worth the ‘EEfRT’? The effort expenditure for rewards task as an objective measure of motivation and anhedonia. PloS one, 4(8), e6598. [PubMed: 19672310]

Treadway MT, Buckholtz JW, Cowan RL, Woodward ND, Li R, Ansari MS, … & Zald DH (2012). Dopaminergic mechanisms of individual differences in human effort-based decision making. Journal of Neuroscience, 32(18), 6170–6176. [PubMed: 22553023]

Wolf AM, & Colditz GA (1998). Current estimates of the economic cost of obesity in the United States. Obesity, 6(2), 97–106.

Wittmann M, Leland DS, & Paulus MP (2007). Time and decision making: differential contribution of the posterior insular cortex and the striatum during a delay discounting task. Experimental Brain Research, 179(4), 643–653. [PubMed: 17216152]

Zelazo PD, & Carlson SM (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. Child Development Perspectives, 6(4), 354–360.

Xu S, Pan Y, Qu Z, Fang Z, Yang Z, Yang F, & Rao H (2018). Differential effects of real versus hypothetical monetary reward magnitude on risk-taking behavior and brain activity. Scientific reports, 8(1), 3712. [PubMed: 29487303]

Author Manuscript
Author Manuscript
Author Manuscript

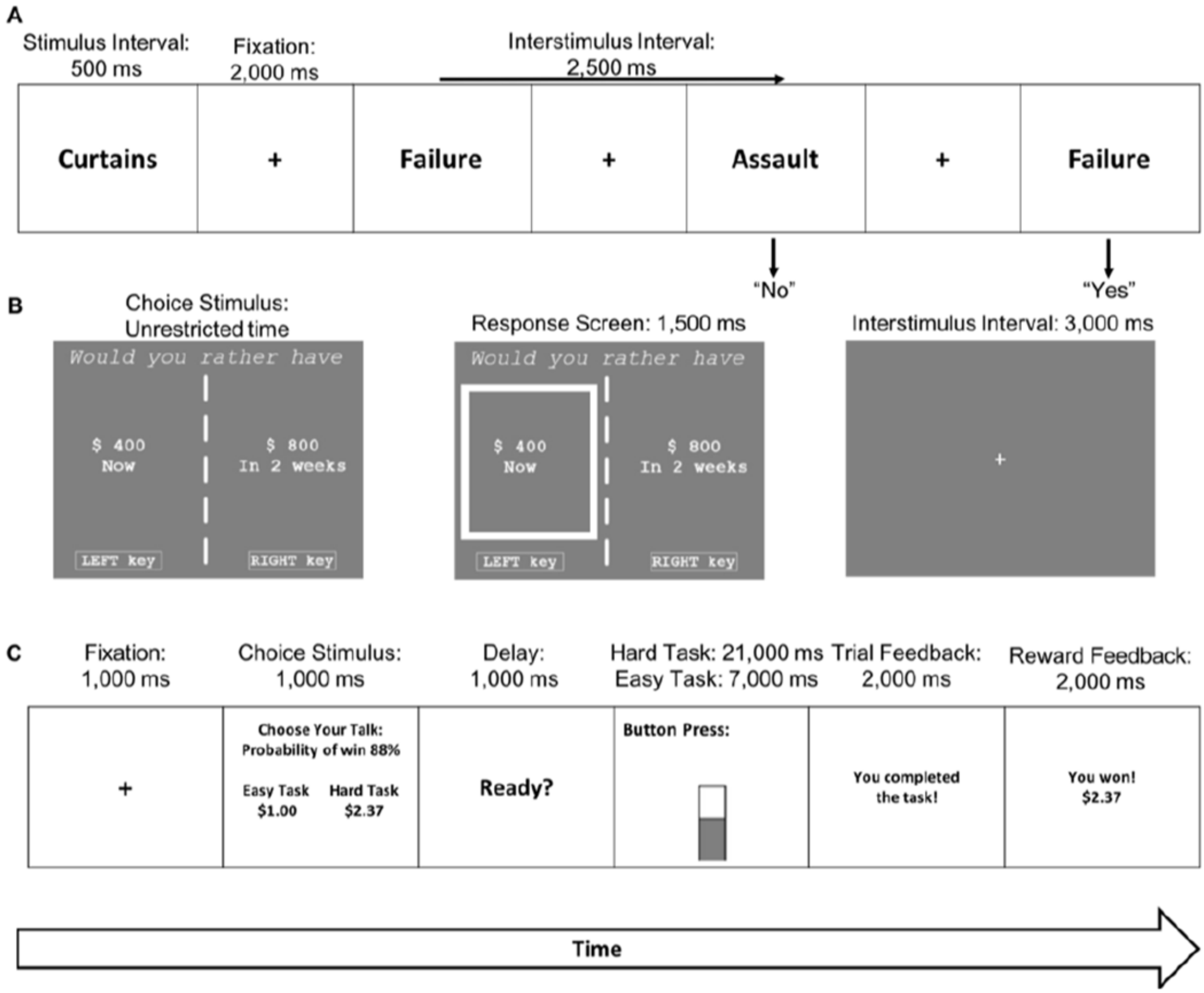

Figure 1.
Task Structure and Stimulus: (A) Affective N-Back Task (B) Delay Discounting Task (DDT) (C) Effort Expenditure for Reward Task (EEfRT)

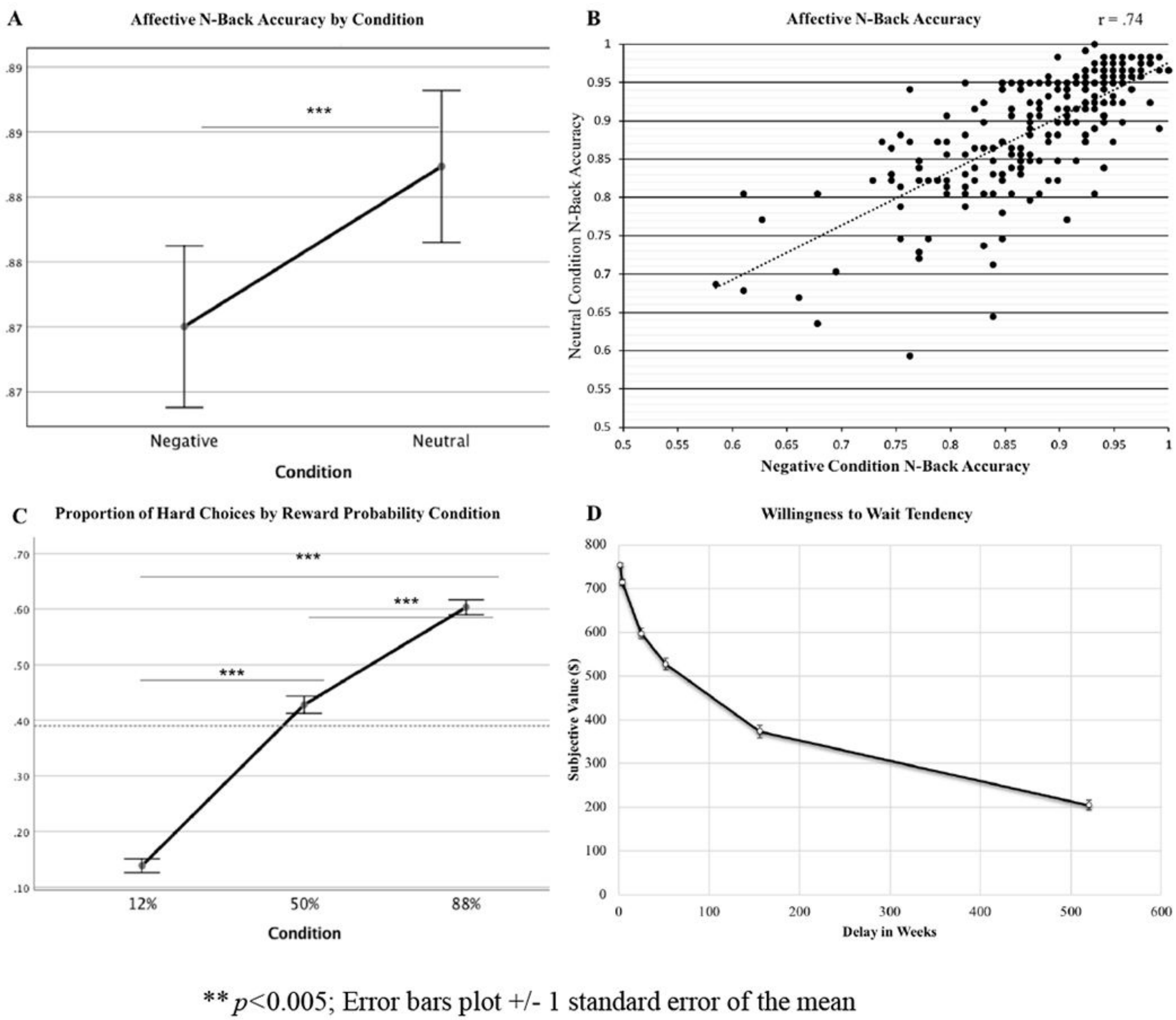

Figure 2.

Main Effect of Condition in the Affective N-back Task (A, B) Effort Expenditure for Reward Task (C), and Delay Discounting Tasks (D): Affective N-Back showed a small but significant difference in accuracy by condition (A) and accuracy was correlated within an individual (B), Willingness to work (percentage of hard choices) significantly differed by reward probability conditions, In the Delay discounting task the subjective value differed by duration of wait (D)

** $p<0.005$; Error bars plot +/− 1 standard error of the mean

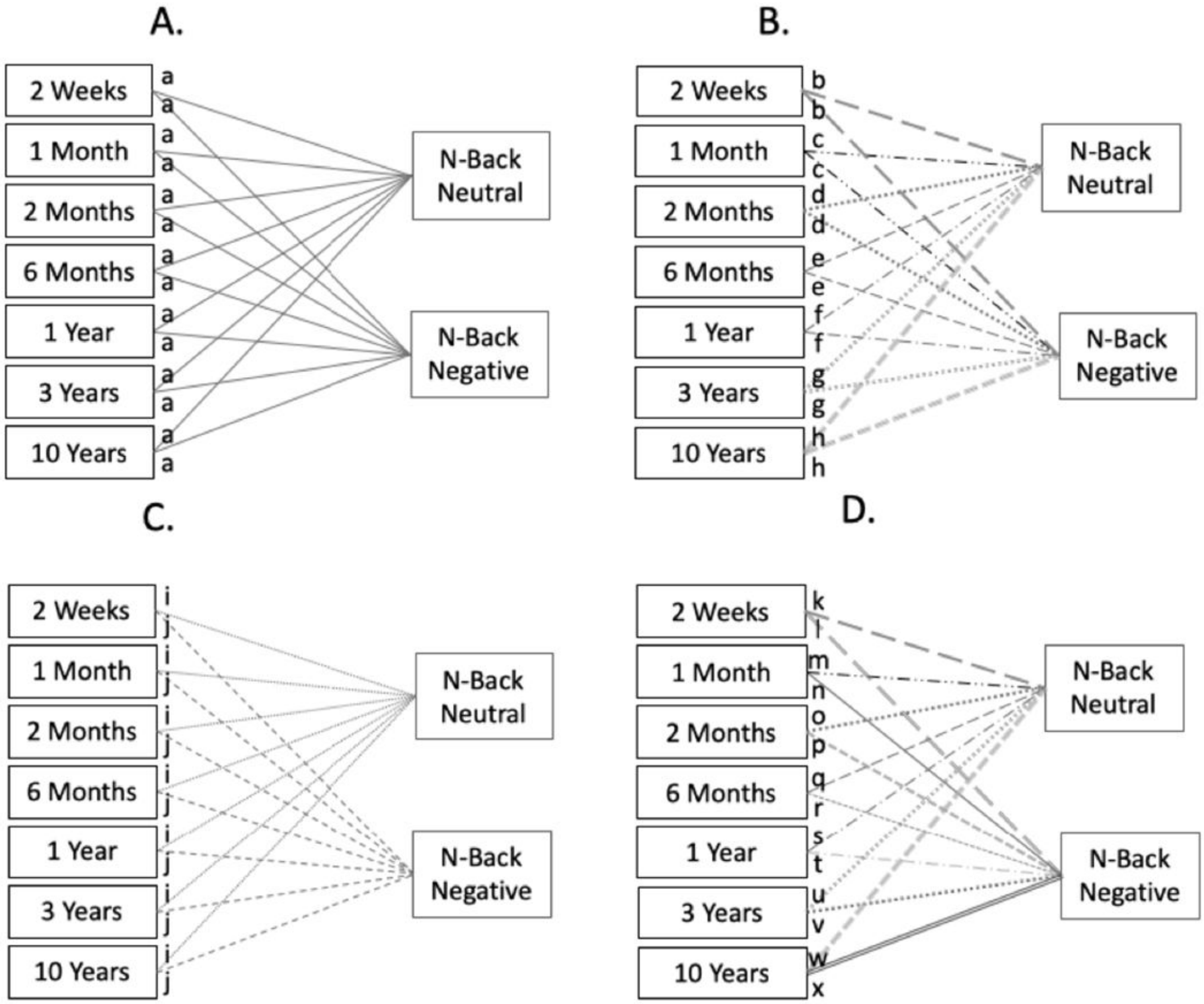

Figure 3.
Willingness to Wait Path Models: A. Model where all relations (blue) are constrained to be one equal value (a); B. Model that constrains the relations of the six time delays conditions to be equal across negative and neutral word N-Back, to be an equal value (b-h), but variables b-h can vary from one another; C. Model that constrains the relations of the Neutral N-Back (purple) to be an equal value (i) across EEfRT conditions and constrains the relations of the Negative N-Back (blue) to be an equal value (j) across DDT conditions, but i and j can vary from one another; D. all paths (k-x) can vary from one another.

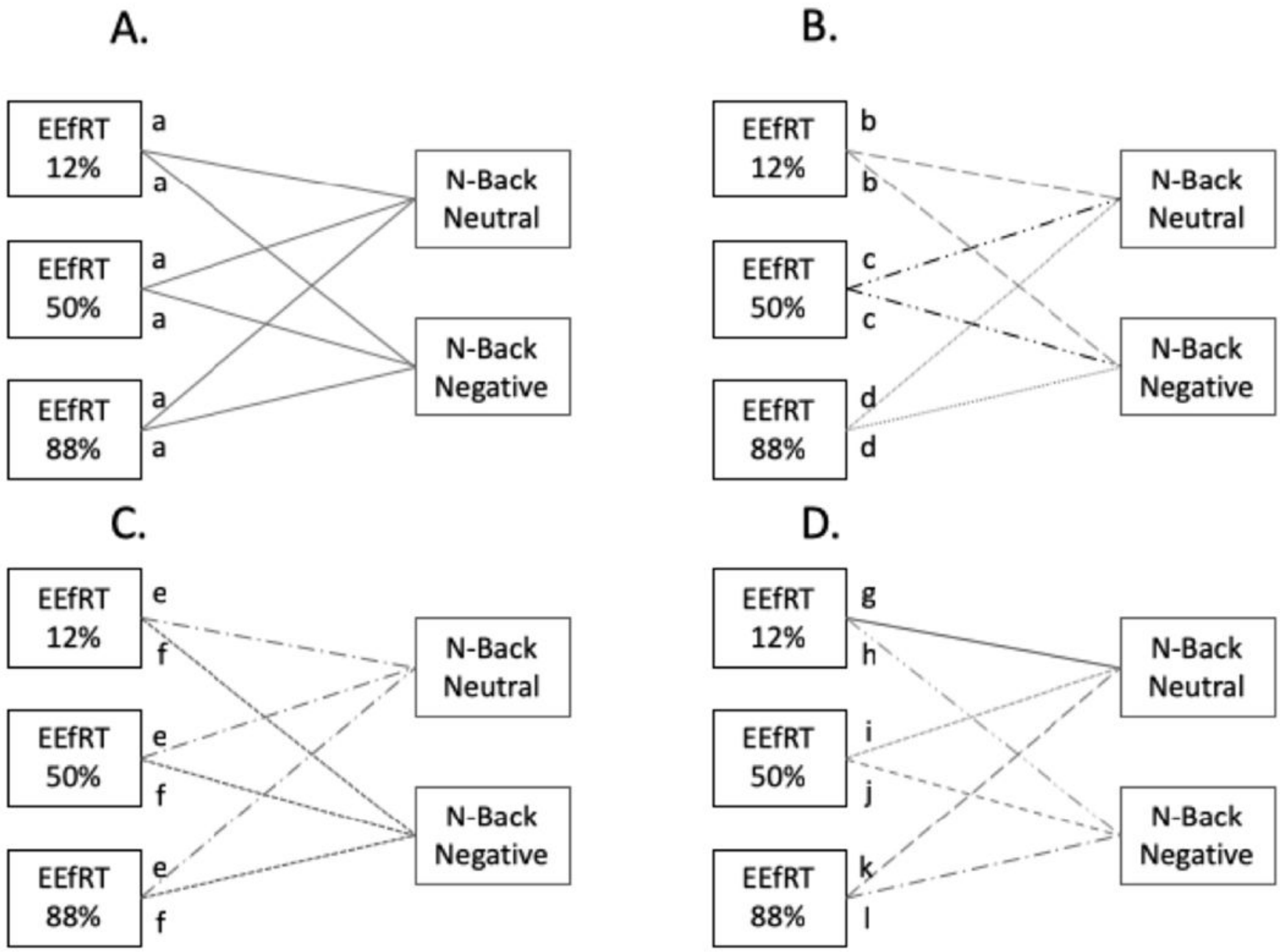

Figure 4.

Willingness to Work Path Models: A. Model where all relations (blue) are constrained to be one equal value (a); B. Model that constrains the relations of the 12% probability of reward condition (orange) to be an equal value (b) across negative and neutral word N-Back, constrains the relations of the 50% probability of reward condition (gray) to be an equal value (c) across negative and neutral word N-Back, constrains the relations of the 88% probability of reward condition (green) to be an equal value (d) across negative and neutral word N-Back, but b, c, and d can vary from one another; C. Model that constrains the relations of the Neutral N-Back (purple) to be an equal value (e) across EEfRT conditions and constrains the relations of the Negative N-Back (red) to be an equal value (f) across EEfRT conditions, but e and f can vary from one another; D. all paths (g-l) can vary from one another.

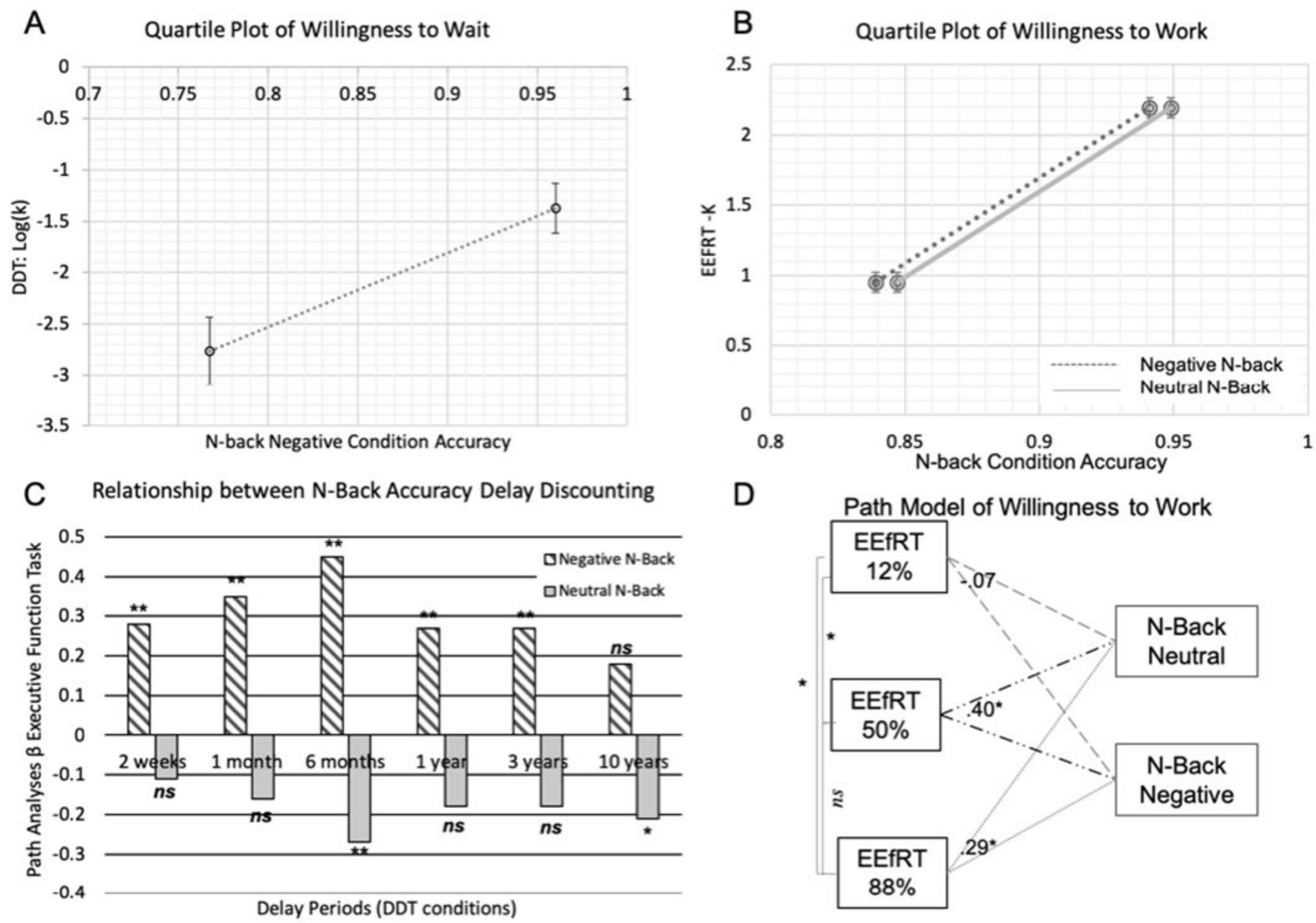

Figure 5.

Affective N-back Task to Delay Discounting Task log(k) (A, C) and Effort Expenditure for Reward Task (B, D): A) Quartile Split (25th and 75th) Comparing Willingness to Wait to Executive Function, B) Quartile Split (25th and 75th) Comparing Willingness to Work to Executive Function C) Plot of Beta weights from Path Analyses Characterizing the Relationship Between Willingness to Work to Executive Function Ability over Delay Conditions D) Path Model with Beta weights Characterizing the Relationship Between Willingness to Wait to Executive Function Ability over Delay Conditions (*n.s.*=not significant, *=$p<0.05$, **=$p<.006$)

Table 1.

Differences by Data Collection Site

	NU *M(StD)*	UCLA *M(StD)*	Statistic	p-value
Age	19.26(0.64)	19.04(0.65)	*t*(227)=2.53	.012 *
Sex	40M/73F	48M/94F	$\chi^2(2)=0.90$	0.64
Affective N-Back Accuracy: Neutral	88.8%(0.07%)	89.5%(0.08%)	*t*(227)=0.75	0.93
Affective N-Back Accuracy: Negative	87.4%(0.07%)	8.88%(0.08%)	*t*(227)=1.31	0.35
DDT k-value	0.23(0.22)	0.16(0.05)	*t*(227)=1.29	.20
EEfRT: Total Hard Choices	39.3%(14.3%)	35.4%(14.2%)	*t*(227)=1.88	0.07
EEfRT: 12% Proportion of Hard Choices	10.7%(16.9%)	11.3%(14.2%)	*t*(227)=0.31	0.76
EEfRT: 50% Proportion of Hard Choices	44.2%(25.4%)	38.2%(22.8%)	*t*(227)=1.88	0.06
EEfRT: 88% Proportion of Hard Choices	57.5%(21.1%)	57.5%(21.1%)	*t*(227)=1.90	0.06

Note: UCLA= University of California, Los Angeles, NU= Northwestern University, M= mean, StD= standard deviation,

* marks comparisons that are significant and survive correction for multiple comparisons

Table 2.

Path Analyses Model Fit Comparisons and the Relationship Between Executive Function to Willingness to Wait and Willingness to Work for Reward by Reward Conditions

Willingness to Wait SEM Model Comparison		**χ^2 Difference**	**χ^2 df Difference**	***p-value***
Model A	Model B	10.31	5	.07
Model A	Model C	5.32	1	.02 *
Model C	Model D	23.16	10	.01 *
	Neutral N-Back Accuracy		**Negative N-Back Accuracy**	
Delay Condition	***β***	***p-value***	***β***	***p-value***
2 weeks	−0.11	.25	0.28	.003 **
1 month	−0.16	.084	0.35	>.001 **
6 months	−0.27	.004 *	0.45	>.001 **
1 year	−0.18	.058	0.27	.006 **
3 years	−0.18	.068	0.27	.005 **
10 years	−0.21	.032 *	0.18	.064
Willingness to Work SEM Model Comparison		**χ^2 Difference**	**χ^2 df Difference**	***p-value***
Model A	Model B	21.03	2	<.0001 **
Model A	Model C	0.33	1	.57
Model B	Model D	1.13	3	.77
	N-Back Accuracy (General)			
Probability Condition	***β***	***p-value***		
12%	−0.07	.33		
50%	0.40	>.001		
88%	0.29	.003		

** Significant p-values .005-.001,

* Significant p-values .01-.006;

DDT = Delay Discounting Task, EEfRT = Effort Expenditure for Reward Task