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# Intertemporal Choices Are Causally Influenced by Fluctuations in Visual Attention

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**Abstract.** Intertemporal discount rates vary widely across contexts and individuals. We propose that a sizable fraction of this variation results from differences in how visual attention is allocated to different features of the decision, such as earlier versus future rewards, and that fluctuations in attentional patterns alter choices. We first tested this hypothesis in an experiment in which participants chose between receiving smaller-sooner versus larger-later monetary rewards while their attention was recorded with eye tracking. We found that cross-participant variation in the allocation of attention explained between 40% and 53% of the individual differences in discounting and that cross-trial variation explained 16% of the participants' propensity to choose the delayed option. To test causality, multiple additional experiments exogenously manipulated the allocation of visual attention and found that shifting attention to attributes that are relatively more attractive in a larger-later option increased patient decision making and altered purchasing behavior. Together, these results are consistent with the existence of a causal impact of visual attention on intertemporal choice and suggest that manipulating attention can have a sizeable impact for important managerial and public policy choice domains.

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## Introduction

Many important decisions involve tradeoffs between earlier and delayed rewards, and sound decision making often requires delaying gratification. Examples include purchasing behaviors (e.g., buy a new laptop today or wait several months for it to significantly decrease in price?), health behaviors (e.g., go to the gym or watch TV at home?), and saving (e.g., buy a new car or save for retirement?). Previous work has shown that we often struggle to delay gratification, that our ability to do so varies across decision contexts, and that there are sizable individual differences in these behaviors (Frederick et al. 2002, Urminsky and Zauberman 2015).

This paper proposes that variation in how visual attention is deployed throughout the choice process can account for a sizable portion of the behavioral differences in discounting, across both contexts and individuals. In particular, we find that contextual variables that shift relative attention toward attributes favoring a delayed option can induce a causal and sizable decrease in discount rates and thus increase an individual's ability to postpone gratification. Additionally, individual differences in attentional

patterns can explain a sizable portion of the differences in discount rates. Although it is unlikely that all discounting behavior operates through this channel, the data here suggest this simple attentional mechanism can have an important impact on intertemporal choice.

To illustrate, consider an individual who plans to purchase a new fashionable outfit and is faced with the decision of making the purchase today or waiting for the outfit to go on sale next month and purchasing it then. If the consumer was to exclusively focus on the amount of money she was asked to spend on the clothes, she would likely prefer to spend less money and hence delay the purchase until the sale was offered. However, if she was to instead focus on when she would be able to wear the outfit, she would likely prefer to have the outfit sooner rather than later and immediately make the purchase. Critically, as we make similar decisions, our attention to the cost of the purchase and the time when the good could be received is likely to vary over the course of the decision. The central idea proposed here is that random fluctuations in how attention is allocated to these attributes may bias decisions toward the option that dominates in a particular attribute category. In this

sense, if attention were shifted to the purchase price rather than the timing of the purchase, the consumer would prefer to delay the purchase as she prefers to spend less money overall.

We report the results of four experiments (and two additional experiments in the online appendix) that explore this relationship between intertemporal decision making and attention. The first experiment combines eye tracking with a common discounting task where participants choose between smaller-sooner and larger-later monetary rewards. We find that up to one half of the cross-participant variation in choices can be explained by differential attention to features of the choice set. Several features of this choice set, the delay date of the smaller-sooner reward and the monetary amount of the larger-later reward, appear particularly influential to decision makers and much of the observed variation in choices can be attributed to time spent attending to these features.

Although this study is suggestive of the main hypothesis, the evidence is correlational. To test for a causal pathway, three additional studies (and two in the online appendix) exogenously manipulate attention and eye fixations in settings that use eye tracking. We find that increasing relative visual attention to attributes that favor a patient choice significantly increases patience across a variety of tasks, including consumer purchasing decisions. Altering attention to choice set features produced a 5%–11% relative shift in the number of patient decisions made across the studies, with larger effects observed among those were closer to indifference in the tasks.

The hypothesis that intertemporal choices are affected by relative attention is important for several reasons. First, most of the existing literature attributes individual differences to variation in fixed discount rates, which are preference parameters that appear hard to change. In contrast, this paper argues that a significant fraction of the within and between participant variation is because of differences in attention. Second, an important goal of this literature is the design of interventions that can alter an individual's ability to delay gratification. Knowing whether changes in attention can have a sizable impact on the likelihood of making a patient choice is useful because *nudging* or *retraining* attention might be easier than changing more hard-wired preference parameters (Camerer et al. 2003, Thaler and Bernartzi 2004, Bernheim and Rangel 2007, Chetty et al. 2009, Thaler and Sunstein 2009). Third, although there is much literature demonstrating that contextual variables matter (Tversky and Kahneman 1974, Johnson and Schkade 1989, Simonson 1989, Read and van Leeuwen 1998, Ariely et al. 2003), we currently lack a systematic understanding for how these variables affect choices. This proposal suggests a critical element of the problem

is to understand how these contextual variables affect attention during the choice process.

## Related Literature

Much literature studies the processes individuals engage in as they make intertemporal decisions. Additionally, much previous work has studied the role of attention in decision making. In this section, we describe closely related work in order to better frame our central question and its potential impact.

Previous work in intertemporal decision making has found that estimated discount rates exhibit a sizable degree of heterogeneity across both individuals and contexts. Across individuals, a number of demographic factors are often correlated with differences in discounting. For example, studies have found that age, education, cognitive ability, and ethnicity are correlated with discount factors (Warner and Pleeter 2001, Frederick 2005, de Wit et al. 2007, Shamosh and Gray 2008, Reimers et al. 2009, Benjamin et al. 2010). In addition to these differences across individuals, the context in which an individual makes a decision is known to affect their discount rate. These contextual findings relate not only to monetary intertemporal decisions, where discounting is higher for shorter than longer delays or for smaller than larger amounts, but also to a large class of common self-control problems (Thaler 1981, Bazerman et al. 1998, Milkman et al. 2009, Urminsky and Kivetz 2014).

Traditionally, the intertemporal choice literature treats observed differences in discounting behavior as fixed differences in underlying parameters of choice models. When modeling intertemporal decisions, one often-used technique is to allow the intertemporal discount factor to follow a specific functional form. Common examples include the exponential (Samuelson 1937), hyperbolic (Mazur 1987), and quasi-hyperbolic (Laibson 1997) discounting models. The discount factor depends on the delay date and at least one additional parameter that describes the speed at which the discount factor changes over time. Hence, when comparing two individuals who behave differently in the same environment or when examining one individual who has varying levels of patience across contexts, the explanation for these behaviors can be explained by changes in an underlying model parameter. In contrast, the proposal here argues that a significant fraction of the differences observed in discounting can be attributed to fluctuations in attention at the time of choice.

Relatedly, a number of psychological mechanisms have been proposed to explain findings in intertemporal choice. A review of these found in Urminsky and Zauberman (2015) summarizes the work on affective determinants, mental representations of the abstractness and concreteness of outcomes, connectedness

of the current and future self, opportunity cost considerations, time perception, and memory queries, as well as others (Thaler and Shefrin 1981; Liberman and Trope 1998; Shiv and Fedorikhin 1999; Kivetz and Simonson 2002; Soman et al. 2005; Weber et al. 2007; Frederick et al. 2009; Bartels and Urminsky 2011, 2015; Herschfield et al. 2011; Spiller 2011; Lempert and Phelps 2016). One mechanism that is particularly relevant to the hypothesis at hand concerns the work from the literature in constructed preferences (Payne et al. 1999). This literature argues that, although choices do reflect some underlying stable preferences, an additional choice component is constructed and used in the choice process at the time that the decision is made. The hypothesis here builds on this literature by suggesting that how visual attention is allocated at the time of choice biases the choice process in intertemporal decision making. Furthermore, the studies here help quantify the extent to which preferences or fluctuations in attention alter choice.

Additional related work has broadly studied the relationship between attention and intertemporal choice, although most of this work has not traditionally used tools that directly measure attention. For instance, it has been proposed that individuals naturally attend to reward magnitudes, rather than associated time delays, and that people's behavior can shift when they are explicitly asked to focus on time delays (Ebert and Prelec 2007). Further work suggests that drawing attention toward the immediate option's opportunity cost can alter patience. For instance, making the hidden zero payments of an intertemporal choice explicit (i.e., reframing the hidden zero question "\$15 today OR \$20 in 7 days" as "\$15 today and \$0 in 7 days OR \$0 today and \$20 in 7 days") has been found to increase patience, although it is unclear whether this effect is purely because of differences in attention as other factors, such as imagination, have been implicated (Magen et al. 2008, 2014; Radu et al. 2011; Jenkins and Hsu 2017; Read et al. 2017).

Although the previous work in intertemporal choice does not explicitly measure visual attention, Franco-Watkins et al. (2015) combine eye tracking with an intertemporal choice task where participants made hypothetical choices over immediate versus delayed gains and losses. Their work explores the typical fixation patterns participants engage in and finds a positive correlation between the time spent attending to a choice option and the propensity to choose that option. Our work expands on these findings in several critical ways. First, our design allows us to analyze the correlation between attention to features of the choice set, such as monetary amounts and delays, and choices, rather than restricting the analysis to only choice options. This allows us to test whether certain attributes of the choice set drive these correlations.

Second, we provide an estimate for the amount of variation in choices, both within and between participants, that is explained by visual attention. Third, we test whether these patterns are causal by carefully manipulating visual attention across five additional studies and two choice domains relating to intertemporal choice. This is particularly important as investigating whether a causal link from attention to choice is partially driving the aforementioned correlations has important managerial and public policy implications.

In additional work, Reeck et al. (2017) found that the search pattern used when making intertemporal choices was associated with and causally influenced patience. Specifically, a comparative search process that acquired information about one attribute and compared it across options increased patience compared with an integrative search process that first acquired information within an option. Khaw et al. (2018) report a related study where participants chose between pairs of delayed payoffs, instead of single delayed outcomes, and found that search patterns predicted patience but the relationship was the opposite to what was observed in Reeck et al. (2017). Although this previous work has focused on how the sequence of attended features impacts patience, the hypothesis here suggests the total time one attends to particular choice set features influences patience. In fact, the studies here demonstrate that even when participants may be prompted to use comparative or integrative search patterns, attention to features of the choice set alter patience under both search strategies. Moreover, the work here provides a conceptual replication of Reeck et al. (2017), in that certain search metrics are correlated with patience, but the data find the relationship between attention and choice is not sizably altered under the different search strategies and that both attention and search jointly predict patience.

Why should attention to particular features of a decision causally influence choices? This prediction follows from models that have been shown to provide quantitatively accurate algorithmic descriptions of the choice process. Examples include the drift-diffusion model (Ratcliff 1978, Ratcliff et al. 2003, Ratcliff and Smith 2004), the leaky-accumulator model (Usher and McClelland 2001), and decision field theory (DFT) (Busemeyer and Townsend 1993, Roe et al. 2001, Busemeyer and Diederich 2002). These types of models have previously been used to explain the psychometric properties of intertemporal monetary choice tasks (Dai and Busemeyer 2014, Rodriguez et al. 2014). All of these sequential sampling models assume that choices are made using a relative value signal that is dynamically computed by integrating instantaneous noisy measures of the desirability of the features associated with the two options and that a



choice is made when the accumulated relative value signal becomes sufficiently strong in favor of one of the two options.

Building on this body of work, additional studies have shown that these algorithms exhibit an attentional bias: options are weighted more heavily while they are attended (Krajbich et al. 2010, 2012; Krajbich and Rangel 2011). Certain specifications of these models assume the allocation of attention to choice set features is independent of the state of the relative value signal and the values of the features themselves. Thus, any variable that shifts attention toward features that favor one of the options increases the probability that it will be chosen.

Evidence consistent with this assumption comes from a broad literature that uses eye tracking to understand how attention is allocated during decision making (Holmqvist et al. 2011; Orquin and Mueller Loose 2013). Importantly, stimulus-driven properties have been found to influence fixations through visual saliency (Milosavljevic et al. 2012), size of display (Lohse 1997, Chandon et al. 2009), and the spatial position of choice options (Sütterlin et al. 2008, Chandon et al. 2009). Goal-directed processes are also known to influence fixations through such processes as varying task instructions (Pieters and Warlop 1999, Glaholt et al. 2010) and underlying object and feature utilities (Bee et al. 2006, Meißner et al. 2016). In fact, recent work has found that a combination of both visual saliency and underlying value information influence fixations (Towal et al. 2013, Mormann et al. 2016). Finally, there is previous evidence for down-stream effects of attention on decision making. For instance, choices can be manipulated by exogenously varying attention (Shimojo et al. 2003, Armel et al. 2008, Pärnamets et al. 2015, Ghaffari and Fiedler 2018) and by altering the underlying visual salience of a choice option (Milosavljevic et al. 2012), lending support to the hypothesis that there is a causal link in both directions between attention and preference.

This paper differentiates itself from the previous findings in several important ways. First, our data support the hypothesis that changes in attention to attributes within an option can impact choices. This finding suggests that choices can be biased toward salient attributes and has important implications for helping individuals make decisions over goods consisting of multiple attributes. Much of the previous work in this area has focused on attentional distributions when individuals are asked to make decisions over a set of several options. Moreover, the results here suggest that even if fixations are largely goal-driven in their location, small fluctuations in their location can have important implications for choice. Second, the design of

the studies here provides evidence that visual attention to particular attributes or options of a choice set can alter decision making. Although a portion of the previous literature makes this implication, several of the causal experimental manipulations here alter fixations to choice attributes and find that doing so biases choices, largely independent of the order in which those features are integrated and attended.

Although the previous information suggests that attention at the time of choice can influence intertemporal preferences, the precise relationship between how attention to specific features of an intertemporal choice set can alter the probability of choosing patiently can take several forms. For example, suppose a decision maker faces an intertemporal choice set consisting of a larger-later option and a smaller-sooner option (e.g., \$15 in 1 day versus \$20 in 21 days). These two options consist of two attributes: monetary amounts and delay dates. Figure 1 summarizes the predictions of two common sequential integration models with attentional biases for such a task. The key differences

**Figure 1.** Two Types of Models and Their Predictions

		Earlier Option	Later Option
Attribute-Based Bias	Amount	↑	↑
	Dates	↓	↓
		Earlier Option	Later Option
Option-Based Bias	Amount	↓	↑
	Dates	↓	↑

*Notes.* Top panel reports predictions for the attribute-based model and the bottom panel reports predictions for the option-based model. Each model contains four regions-of-interest (ROIs), which are generated by interacting the option in columns (earlier option or later option) with the attribute type in rows (amounts or dates). The top left box refers to the earlier amount ROI, top right refers to the delayed amount ROI, bottom left refers to the earlier date ROI, and bottom right refers to the delayed date ROI. Arrows indicate how shifting attention to that ROI will impact the probability of making a patient choice. Arrows pointing upward indicate an increase in the probability of choosing patiently, and downward pointing arrows indicate a decrease in this probability.

between models relates to the exact form of attentional biases.

One class of models states that there is an attribute-based bias, so that fixating on a particular attribute increases the instantaneous relative weight of that attribute for both options equally (Dai and Busemeyer 2014, Scholten et al. 2014, Cheng and Gonzalez-Vallejo 2016). This implies that amounts have a higher relative weight during fixations to the earlier amount or the later amount and a lower relative weight during fixations to the earlier date or later date. As summarized in the top panel of Figure 1, this predicts that shifts in relative attention toward the earlier amount or later amount should increase the likelihood of making a patient choice, whereas shifts in relative attention toward the earlier date or later date should decrease it. For example, fixating to either amount feature increases the relative weight of the amounts, which results in an increased probability of choosing patiently given that the patient option has a larger monetary amount.

Another class of models states that there is an option-based bias, so that fixating on either attribute of a particular option increases the weight given to all the features associated with that option, relative to the features of the other option (Samuelson 1937, Ainslie 1975, Laibson 1997, Scholten et al. 2014). As summarized at the bottom of Figure 1, this predicts that shifting attention toward the later amount or later date should increase the likelihood of making a patient choice, whereas shifting attention toward the earlier amount or earlier date should decrease it.

We note several important features about these models. First, the two models both predict that shifting attention toward the later amount should increase the probability of making a patient choice, whereas shifting attention toward the earlier date should decrease it. In contrast, the predictions for shifting attention to the later date or earlier amount depend on which type of attentional bias is dominant. Second, there are other potential models that could be at work in intertemporal choice. For example, if delay dates operate as an aversive attribute, then it is possible that increasing attention to a delay date can accentuate its negative value (Smith and Krajbich 2018). In such a case, increasing attention to the earlier date would increase the probability of making a patient choice because evidence against the earlier option is being integrated during fixations to the earlier date; likewise, increasing attention to the later date would decrease the probability of making a patient choice. Whereas the models highlighted here are not an exhaustive list of possibilities, they represent possibilities inspired by previous work that could be present in intertemporal choice.

Although the previous models hypothesize different relationships between attention to a feature and

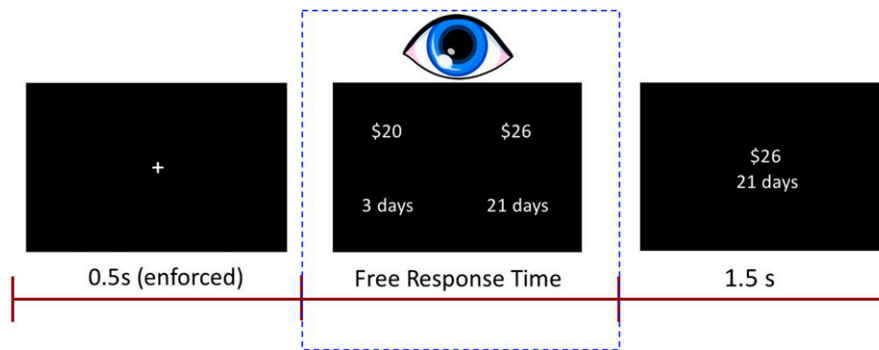
the probability of making a patient choice, it is also relevant to discuss the predicted magnitude of each relationship. Certain specifications of both the attribute and option-based models depicted in Figure 1 would predict that attention to the later amount or the earlier date would have a more sizeable impact on choice than attention to the earlier amount or later date. To see why, note that it is desirable to (1) receive more money and to (2) receive it at an earlier date. Furthermore, suppose the relative value for an option is dynamically computed by integrating noisy measures of the desirability of different features and there is an attentional bias such that the attended feature is weighted more heavily than unattended features, as predicted by the previous sequential sampling models. Then, because the value of the later amount (earlier date) is greater than the value of the earlier amount (later date), one should find a stronger relationship between attention to the more desirable feature of each attribute or option and choice. The logic here is that because the later amount and earlier date are the most desirable features in both their attribute and alternative, fixating to them provides a faster accumulation of the relative decision value to a choice barrier compared with fixating to the less desirable feature. This suggests that there might be a larger effect of shifting attention to the later amount and earlier date compared with the earlier amount and later date.

## Study 1: Correlational Test

Experiment 1 (Figure 2) combines a standard intertemporal monetary choice paradigm with eye tracking to address the following three questions. First, is there a correlation between attention, as measure by fixations, and choices in intertemporal decision making? Second, are cross-trial fluctuations in relative attention associated with sizable changes in the likelihood of making a patient choice? Third, what fraction of the individual differences in discount rates can be explained by attentional differences?

## Methods

**Task.** Forty-three participants completed 216 trials of an intertemporal monetary choice task. In each trial, participants first viewed a fixation cross at the center of the screen and were asked to fixate on it for 500 ms. Compliance was monitored with the eye tracker so that the trial proceeded to the next stage only after 500 ms of continuous fixation. The duration of the initial fixation was enforced to ensure that participants began every choice trial by fixating at the center of the screen. Next, participants were shown a choice screen in which they had to choose between receiving a smaller, sooner monetary reward and a larger, later alternative. Participants had as long as they needed to

**Figure 2.** (Color online) Trial Structure for Study 1

*Notes.* Every trial, participants first stared at the central fixation cross for 500 ms. Afterward, the choice set was revealed, and participants had as long as they liked to make a choice between an option to be received today and an option to be received at some future date. Eye fixations were recorded at this point. After entering a response, participants saw feedback for 1.5 seconds and then moved to the next trial.

decide and indicated their choice by pressing either the left or right buttons on a keyboard with their dominant hand. Afterward, participants saw a 1.5-second feedback screen that depicted their choice. Trials were separated by a two-second black screen.

At the end of the experiment, one trial was selected at random, and the participant's choice in that trial was implemented. This trial was determined by having the computer randomly choose a trial number. After determining the payments, participants completed a short questionnaire largely designed to investigate payment beliefs, and responses reported in the online appendix suggest that participants largely believed the payment promises. To minimize differences in transaction costs or credibility between earlier and delayed payments, payments were implemented via PayPal with payments sent at the appropriate delay. In addition, regardless of the delay, participants received an email at the time their PayPal account had been credited. The average total payment was \$31 (SD = \$7).

The choice screens were constructed as follows. The location of the monetary amounts (range: \$17–\$60) and delays (range: 0–207 days) were randomized by trial so that one appeared at the top of the screen and the other appeared on the bottom of the screen. Each trial included an earlier option with a delay of  $D_1$  days and always denoted as  $D_1$  days, where  $D_1$  ranged from 0 to 7. The other delay was given as  $D_2$  days, where  $D_2$  ranged from 7 to 207. The size of the delayed monetary amount was constrained to be at least as large as the sooner amount. The order of the questions was randomized for each participant, the location (left or right-hand side) for the sooner and delayed options was randomized every trial, and the location (top or bottom) for the monetary amounts or time delays was randomized every trial. The attribute values used in the 216 trials were identical across all participants, and the full stimulus set with choice probabilities is reported in Table A1 of the online appendix.

**Eye Tracking.** Eye movements were recorded at 1,000 Hz using an SR Research Eyelink 1000 Plus desktop-mounted eye tracker with a chin rest, and the experiment took place in a laboratory room used for eye tracking and other experiments. The eye tracker recorded throughout each trial and produced a time series consisting of fixation locations and durations using the SR Research software. Participants were required to keep their dominant hand on the response buttons throughout the task. This was done to eliminate eye movements related to the motor implementation of the choice, as opposed to the choice process, which is our object of interest. All participants reported having normal or corrected to normal vision as specified by the recruitment criteria.

In order to ensure the eye tracker was able to successfully track each participant's gaze, we used a 13-point calibration exercise. Participants initially fixated to 13 points on the computer screen, which was immediately validated by having them refixate to the same points. This procedure was automated by the eye tracking software, which examined the difference between the validated and initial calibration. The software assigned a rating of good, fair, or poor to the validation. Only participants who received a rating of good, which suggests a minimal difference in calibrations, were able to complete the study. Additionally, every 50 trials, participants were informed how many trials in the choice task they had completed and took part in a calibration drift check to ensure their calibration had not severely degraded over the course of the experiment. All participants passed such a drift check at each prompting.

We focus the analyses on the fixation locations during the choice screens. In particular, we measured the amount of time during choice that was spent looking at each of the four regions-of-interest (ROIs): earlier amount, earlier date, delayed amount, and delayed date. To do this, we first identified the center

of each ROI and then added 125 pixels around the center of each ROI. The text for the ROIs was centered at locations (384, 216), (384, 864), (1536, 216), and (1536, 864) (coordinates in pixels based on a screen resolution of  $1,920 \times 1,080$  with the top left coded as (0, 0)), which allowed for ROIs to extend beyond stimuli to account for noise between the true and recorded fixations.

For every participant and trial, we computed the amount of time spent looking at one of the four ROIs. We then determined the relative time spent looking at each ROI by dividing the time spent looking at each ROI by the total time spent looking at all four ROIs for every trial. This measure allows for an accurate comparison of data between participants who may have different response times. In many of the following analyses, we supplement this measurement with absolute time to an ROI (as measured in seconds) or the number of fixations made to an ROI.

**Estimating Discount Rates.** We used two different measures of the intertemporal discount rate. First, for every participant, we computed the fraction of time the delayed option was chosen, which we refer to as a patient choice.

Second, for each participant, we estimated the discount rate that best explains the choice data using a hyperbolic model. We use the method proposed in Chabris et al. (2008), which is frequently used in the literature. The method assumes that participants make choices by computing a value for each option and then comparing them. The value of receiving \$Y in  $D_2$  days is assumed to be  $\frac{\omega Y}{e^{1+kD_2}}$ , where  $k$  is a discount parameter controlling the participant's patience: a low  $k$  signifies patient decision making, and a large  $k$  signifies impatient behavior. Participants then choose the delayed option with probability

$$\frac{\frac{\omega Y}{e^{1+kD_2}}}{\frac{\omega X}{e^{1+kD_1}} + \frac{\omega Y}{e^{1+kD_2}}},$$

where  $X$  is the monetary amount offered in the earlier option and  $D_1$  is its associated delay. The parameter  $\omega$  controls the amount of the noise in the choice process: choices are fully random when  $\omega = 0$ , and their sensitivity to value differences increases with  $\omega$ . For every participant, we used maximum likelihood estimation to estimate the  $\hat{k}$  and  $\hat{\omega}$  parameters that best explain the choice data.<sup>1</sup>

## Results

**Choices.** Participants chose the patient option 42.6% of the time (SD = 34.5%). A histogram of participant's patient choices appears in Figure A1 of the online appendix and finds that approximately 40% of the

participants displayed an intermediary level of behavior by choosing the patient option greater than 20% but less than 80% of the time. The average value of the estimated hyperbolic discount parameter,  $k$ , was 0.019 (SD = 0.020), which is comparable with previous results using this estimation procedure. Both indices provide a measure of the extent to which participants discount future rewards and from regressing  $k$  on the fraction of patient choices made, the two measures are significantly correlated ( $\beta = -0.05$ ,  $p < 0.001$ ;  $r = -0.90$ ). Table A2 in the online appendix reports model estimates and goodness of fit tests by participant. Additionally, the hyperbolic model makes the same prediction as the observed choice data in 89.1% (SD = 9.7%) of trials and fits better than an exponential discounting model, suggesting the model accurately fits the data. For robustness, we report results using both choice measures. When comparing initial versus later choices, there was no difference in terms of the propensity to choose the patient option or how well the model predicted choices, as described in the online appendix. As this suggests, there was significant variation in discount rates between participants (percent patient: max = 96.3 min = 0.5,  $k$ : max = 0.05, min = 0.0001), which we exploit in several of the analyses below.

**Response Times.** Participants took an average of 2.5 seconds to make a decision (SD = 0.9 seconds). We estimated a linear mixed-effects regression of response time on trial difficulty, which in this and all future similar analyses included random slopes and intercepts, unless otherwise specified. Consistent with the predictions of sequential integration models of choice, we found that response times increased with difficulty ( $\beta = -0.048$ ,  $p < 0.001$ ), where difficulty was defined as the absolute value of the difference between the future reward under the hyperbolic model and the value of the earlier reward under the hyperbolic model. As detailed in the online appendix, participants became faster in responding, but the difference in response times was relatively small and difficulty remained significant even after controlling for trial number.

**Average Fixation Patterns.** We used fixations to each of the four ROIs as a measure of attention to the individual features. Although it is well known that it is possible to attend to information without fixating on it, as demonstrated in the literature on covert attention (Posner et al. 1977, Egly et al. 1994), it appears unlikely that there is a large dissociation between the two in this task.<sup>2</sup>

Participants made an average of 6.0 fixations per trial (SD = 1.8), which implies that, on average, they fixated to the ROIs displaying the different attributes



more than once. A linear mixed-effects regression found the number of fixations increased with trial difficulty ( $\beta = -0.10$ ,  $p < 0.001$ ).

Table 1 summarizes the relative fixation time patterns across the four ROIs. Participants spent more time looking at the upper fields than at the lower fields, despite the fact that the location of the amount and delay features were randomized over trials ( $t(42) = 4.76$ ,  $p < 0.001$ ). Furthermore, participants spent more time fixating to the left than the right-hand locations ( $t(42) = 2.37$ ,  $p = 0.022$ ) and participants spent more time attending to the delayed option than the earlier option ( $t(42) = 4.31$ ,  $p < 0.001$ ). As reported in the online appendix, the distribution of relative attention to the ROIs was not significantly different for faster versus slower decisions. Finally, there was significant trial-to-trial variation for all ROIs, a fact that we exploit in the within participant analyses below. Table A3 in the online appendix reports the average number of fixations to each ROI.

**Table 1.** Total Fixation Time to Each ROI

Panel A: Spatial			
	Left	Right	Left + right
Up	28.5 (3.8)	26.4 (6.1)	54.9 (6.8)
Down	23.4 (4.6)	21.6 (3.5)	45.1 (6.8)
Up + down	51.9 (5.3)	48.1 (5.3)	
Panel B: Feature of interest			
	Earlier	Delayed	Earlier + delayed
Amount	25.1 (3.2)	26.4 (5.6)	51.5 (8.3)
Delay	22.6 (5.1)	25.9 (4.0)	48.5 (8.3)
Amount + delay	47.7 (3.5)	52.3 (3.5)	
Panel C: Standard deviation			
	Earlier	Delayed	
Amount	11.1 (3.5)	11.5 (3.8)	
Delay	10.8 (3.5)	11.4 (3.7)	

*Notes.* Total fixation time to each ROI. (A) The mean percent of total fixation time that was spent attending to each region of interest split by the spatial orientation of the screen: columns are horizontal orientation and rows are vertical orientation. (B) The mean percent of total fixation time that was spent attending to each region of interest split by feature of interest: columns are the earlier and delayed options and rows are monetary amounts and delay dates. (C) Reports the mean standard deviation over participants from B. Means are taken over participant-specific standard deviations, and standard deviations appear below in parentheses.

Table 2 summarizes the pattern of first fixation locations across the four ROIs. The majority of first fixations were to the top-left location ( $t(42) = 11.49$ ,  $p < 0.001$ ), although the first fixation locations are more balanced when analyzed by feature of interest. There was no bias toward first looking at the delayed option ( $t(42) = 1.41$ ,  $p = 0.166$ ), which suggests that participants were unable to identify the location of the delayed option through peripheral vision and use such information to influence the location of their first fixation before the information in the ROIs had been sampled.

**Within-Participant Analysis.** As shown in Table 1, relative fixations varied significantly from trial to trial. Here, we investigate if this variation is associated with changes in the likelihood of making a patient choice and if these changes are consistent with the predictions described above. Additionally, we quantify the size of these effects.

To do this, for each ROI, we estimated a random-effects logistic regression where we regressed a binary variable for whether the patient option was selected on the fraction of time spent fixating on a particular ROI. This was done in a separate regression for each ROI because the relative attention measures are not independent across ROIs, although the fifth column includes all ROIs without a constant. Thus,

**Table 2.** Percent of First Fixations to Each ROI

Panel A: Spatial			
	Left	Right	Left + right
Up	72.1 (26.9)	15.2 (22.1)	87.3 (14.8)
Down	9.4 (13.3)	3.3 (6.3)	12.7 (14.8)
Up + down	81.5 (25.1)	18.5 (25.1)	
Panel B: Feature of interest			
	Earlier	Delayed	Earlier + delayed
Amount	25.2 (1.8)	23.6 (2.4)	48.7 (2.3)
Delay	24.3 (2.4)	26.9 (2.5)	51.3 (2.3)
Amount + delay	49.5 (2.3)	50.5 (2.3)	

*Notes.* Percent of first fixations to each ROI. (A) The mean percent of first fixations that were made to each region of interest split by the spatial orientation of the screen: columns are horizontal orientation and rows are vertical orientation. (B) The mean percent of first fixations that were spent attending to each region of interest split by feature of interest: columns are the earlier and delayed options and rows are monetary amounts and delay dates. Means are taken over participant-specific means, and standard deviations reported below in parentheses.

each regression should be interpreted as estimating the effect of shifting relative attention to the target ROI while reducing relative attention on the other ROIs proportional to their average frequencies. This analysis is supplemented by varying the dependent variable from relative attention to absolute attention in the right-hand column, and the online appendix reports results using the number of fixations to an ROI rather than time to an ROI. Although the results are largely consistent across attention metrics, we focus on the relative and absolute time rather than fixation count as the models described previously that inspire this analysis also focus on fixation time, and there is no sizable correlation between fixation count and duration, as detailed in the online appendix.

Furthermore, for each ROI, we computed the mean predicted impact of shifting relative attention in that ROI from the 10th to the 90th percentile of the observed distribution of relative attention on the probability of choosing the patient option. To calculate this, we first sampled random trial numbers 1,000 times for each participant and ROI, with replacement. For each of the random trial numbers, we extracted the fraction of time the participant spent attending to the ROI in that trial and used the participant-specific estimated regression weights from the mixed-effects model to calculate the probability that the participant chose the patient option in that trial. Finally, we calculated the 10th and 90th percentile of the distribution of the probability of a patient choice for each participant and report the mean change over all participants, which we denote as the mean effect size. A positive effect size denotes an average increase in patience, whereas a negative effect size denotes an average decrease in patience.

Table 3 summarizes these results. Consistent with the predictions, increases in attention to the earlier date were correlated with a decreased likelihood of choosing the patient option and increases in attention to the delayed amount had the opposite effect. Importantly, the predicted effect sizes were substantial. For example, a shift from the 10th to the 90th percentile of the observed distribution of relative attention to the earlier date decreased the probability of making a patient choice by 16%, as given by the mean effect size. The relationship between attention to the earlier amount and patience was not statistically significant, but the significance of the correlation between attention to the delayed date depended on the attentional metric used. Notably, the coefficients on the delayed amount and earlier date are significantly larger than the coefficients on the other features, as reported in the online appendix. Overall, the results suggest that attention to the feature in which an attribute dominates is strongly associated with choices, whereas attention to other features may have a weaker impact.<sup>3</sup>

**Table 3.** Within-Participant Impact of Attention

ROI	Coefficient estimates					
	Relative attention					Absolute attention
Constant	−0.50 (0.35)	−1.79** (0.34)	0.69 (0.37)	−0.92* (0.39)	—	−0.98* (0.48)
Earlier amount	−0.66 (0.46)	—	—	—	−1.14* (0.47)	−0.22 (0.13)
Delayed amount	—	4.15** (0.61)	—	—	2.22** (0.75)	1.57** (0.25)
Earlier date	—	—	−6.27** (0.68)	—	−5.45** (0.63)	−2.36** (0.53)
Delayed date	—	—	—	0.89 (0.53)	0.72 (0.48)	0.86** (0.17)
Mean effect size	−0.02	0.13	−0.16	0.03	—	—

*Notes.* Each column reports the results of a logistic mixed-model regression where an indicator variable for making a patient choice was regressed on a constant and the measurement of attention to the ROI. Mean effect sizes denote the predicted effect of shifting relative attention toward each attribute, from the 10th to the 90th percentile.

Several additional robustness checks appear in the online appendix. Potentially the most of relevant of these omits the final fixation from the analysis. If the gaze cascade effect (Shimojo et al. 2003) was driving the previous results, one would expect the final fixation in each trial to strongly influence the previous analysis; however, after applying a highly conservative test for such an effect by omitting the entire final fixation, the main results on the delayed amount and earlier date hold. Across all attention metrics, the delayed amount is positively correlated with patience, and the earlier date is negatively correlated with patience, whereas no other feature has a significant correlation with patience. The remainder of the robustness checks discussed in the online appendix largely suggest that this main result holds under a number of restrictive circumstances.

**Between-Participants Analysis.** Next, we tested whether between-participant differences in attention could explain a substantial fraction of the individual variation in discount rates. To do this, we first computed the average amount of attention that each participant paid to each of the four ROIs. For each ROI, we estimated a linear regression of the participant-level measure of patience (either fraction of patient choices or  $k$ ) on the participant-level measure of attention paid to the ROI.

Table 4 reports the results. We found a positive correlation between relative attention to the delayed amount and the likelihood of making a patient choice, and a negative correlation between relative attention to the earlier date and the likelihood of making a

**Table 4.** Between-Participant Impact of Attention

	Coefficient estimates					
ROI	Relative attention				Absolute attention	
Panel A: Fraction patient						
Constant	−0.54 (0.40)	−0.63** (0.20)	1.53** (0.17)	1.08** (0.33)	— —	0.61** (0.12)
Earlier amount	3.83* (1.56)	— —	— —	— —	−0.43 (1.59)	0.01 (1.19)
Delayed amount	— —	3.99** (0.73)	— —	— —	2.42 (1.24)	1.52 (0.97)
Earlier date	— —	— —	−4.90** (0.74)	— —	−4.32** (1.22)	−4.00** (0.97)
Delayed date	— —	— —	— —	−2.52 (1.27)	3.37** (1.09)	1.40 (0.77)
$R^2$	0.13	0.42	0.52	0.09	—	0.53
Panel B: Estimated $k$						
Constant	0.06 (0.02)	0.08** (0.01)	−0.03** (0.01)	−0.00 (0.02)	— —	0.02** (0.01)
Earlier amount	−0.18 (0.09)	— —	— —	— —	0.11 (0.09)	0.04 (0.07)
Delayed amount	— —	−0.22** (0.04)	— —	— —	−0.11 (0.07)	−0.13* (0.06)
Earlier date	— —	— —	0.27** (0.04)	— —	0.30** (0.07)	0.18** (0.06)
Delayed date	— —	— —	— —	0.11 (0.07)	−0.18** (0.06)	−0.06 (0.05)
$R^2$	0.09	0.40	0.50	0.05	—	0.48

Notes. Each column reports the results of a linear regression where participant-specific measures of patience (top = mean fraction of patient decisions, bottom = estimated  $\log(k)$ ) were regressed on the average time that each participant spent attending to particular ROIs. The slopes and constants from each regression are reported, with standard errors below in parentheses.

\*\*and \*denote significance at the 1% and 5% levels, respectively.

patient choice. In contrast, attention to the later delay was not significantly correlated with individual differences in discounting. The significance of attention to the earlier amount depended on the measurement of behavior used as the dependent variable, though in both cases the proportion of variance explained by this attribute is smaller than both the delayed amount and earlier delay. Because the participant-level measures of attending to the different ROIs are correlated (min = −0.89, max = 0.36), we also estimated a linear model in which the four attentional measures were included. As shown in the fifth column of Table 4, although several regions of interest remain significant, attention to the earlier date is the most strongly correlated with individual differences in discount rates after controlling for these factors. Furthermore, these results largely hold when using absolute rather than relative attention: the earlier date is negatively correlated with patience while the delayed amount is positively associated with patience when the dependent variable is the estimated  $k$  but does not reach significance for the fraction of patient choices

metric, although the sign of the effect is in the same direction. Table A15 in the online appendix finds similar results when fixation count is the measurement of attention.

Two aspects of these results are worth highlighting. First, the results suggest that between 40% and 53% of the individual differences in discount rates can be explained using differences in the average relative propensity to look at different ROIs. Second, the results across participants are consistent with those found in the previous section; in both cases, the attentional variable that has the largest impact in explaining variation in patience is visual attention to the earlier delay, followed by the propensity to look at the delayed amount. This supports the hypothesis that as attention fluctuates throughout the course of a decision, the attributes that are most favored in a class (i.e., receiving money earlier or receiving more money) act to bias choice.

Several robustness checks appear in the online appendix. An analysis that omits the final fixation from the analysis in Table 4 and finds a significant relationship between attention to the earlier date and patience.

The remainder of the robustness checks discussed in the online appendix largely suggests that the previous results hold under a number of restrictive circumstances.

**Changes in Fixations Across Trials.** An important assumption of the models motivating the hypothesis tested here is that the allocation of attention is largely exogenous to the state of the choice process and to the value of the attributes. More concretely, these models assume that fixations can be modulated by visual features of the stimuli (e.g., text versus numbers or spatial location), but not by the state of the relative value signal that drives the choice or by the absolute or relative value of the attributes. This assumption is important because it implies that fluctuations in attention have a causal impact in the choice process instead of being driven by it.

Testing these assumptions regarding the orthogonality of attention directly is difficult, because it requires having a measure of the relative value signal's state before a choice is made, which is quite challenging to obtain, and because attention terminates at the end of the choice process, which can produce spurious correlations between attentional measures and attribute values. One way to address these issues is to carry out external manipulations of attention, as reported in the additional studies in the manuscript. However, because these manipulations also have limitations, we finished the analysis of study 1 by carrying out an indirect test of the orthogonality of attention.

The logic of the test is as follows. From the choice data, we know that the feature values are correlated with the likelihood of choosing the patient option. Specifically, the delayed monetary amount and earlier date are positively correlated with choosing the patient option, and the earlier monetary amount and delayed date are negatively correlated with choosing the patient option. Under the maintained hypothesis that choices are compatible with a sequential integration model, this implies that, on average, each of these variables should also be correlated with the state of the integrator across trials. Thus, if fixations were driven mostly by the state of the relative value signal, one would expect a strong association between the relative fixations and the attribute values across trials. To examine this, we ran a series of linear mixed-effects regressions of the relative time that was spent attending to each ROI on the value of the choice set features.

Table 5 reports the results of this test. Importantly, in all cases, the magnitude of the effects was quite small in size, contrary to what would be expected if attention were guided mostly by the state of the relative value signal or by the relative value of the features. To quantify this, Table 5 also reports an estimate of the effect size or the maximum percentage change in attention to each ROI that could be induced as a feature ranged from its minimum to maximum values, which were also found to be relatively small.<sup>4</sup> Robustness checks in the online appendix find a similar result when the measurement of attention is absolute attention or fixation count. There is still a

**Table 5.** Impact of Attribute Values on Relative Attention

	Earlier amount	Delayed amount	Earlier date	Delayed date
Constant	0.222	0.266	0.239	0.274
	25.09	23.32	23.20	28.51
Earlier amount	0.001	−0.001	0.001	−0.001
	3.18	−2.76	3.22	3.30
	<b>1.5%</b>	<b>−1.3%</b>	<b>1.4%</b>	<b>−1.6%</b>
	−0.000	0.001	−0.002	0.000
Delayed amount	−0.03	4.81	−6.39	2.34
	<b>−0.0%</b>	<b>4.7%</b>	<b>−6.6%</b>	<b>2.0%</b>
	−0.001	−0.001	0.002	0.000
	−1.33	−1.95	3.05	0.01
Earlier date	<b>−0.6%</b>	<b>−0.7%</b>	<b>1.3%</b>	<b>0.0%</b>
	0.000	−0.000	0.000	0.000
Delayed date	1.42	−3.84	1.00	1.01
	<b>0.9%</b>	<b>−2.1%</b>	<b>0.5%</b>	<b>0.7%</b>

*Notes.* Each column reports the results of a linear mixed-effects regression. In each case, the dependent variable was the fraction of time attending to the ROI, and the independent variables were a constant, the earlier monetary amount offered, the delayed monetary amount offered, the earlier date, and the delayed date. For each independent variable, coefficients and *t*-statistics from the regression are reported in the first two rows for each coefficient. For all independent variables, excluding the constant, a measure of effect size appears in bold in the third row. This effect size measures the average change in the fraction of time attending to each ROI, as the corresponding variable increases from the minimum amount shown to participants to the maximum amount shown to participants.



quantitatively small relationship between feature values and attention, and this holds even in the first several trials of the experiment.

Together, these analyses provide support for the hypothesis that some of the variation in attention is exogenous to the attribute values and to the comparison process used to make the choice. However, these tests cannot rule out the possibility that some of the attentional variation is endogenous, which highlights the importance of the following experiments where attention is manipulated exogenously.

Before presenting the results of these experiments, we report an analysis that exploits the design of the current study in order to directly test the causal role of attention. Specifically, as reported earlier, participants paid the most attention to the top left feature of the choice set and the least attention to the bottom left feature. This provides a source of exogenous variation that can influence patience: when the delayed amount (earlier date) was in the top left it received more attention than the earlier date (delayed amount), which was located in the bottom right. Although this is a subtle manipulation compared with the additional studies reported later in the paper, there was marginal evidence to suggest the spatial location of the features alters patience. Participants chose patiently 43.1% (SD = 35.7%) of the time when the delayed amount was in the top left, and 41.6% (SD = 34.4%) of the time when the earlier date was in the top left ( $t(42) = 1.80, p = 0.079$ ). In the later studies, we exogenously manipulate attention to features of the choice set using carefully constructed paradigms that use the eye-tracker to enforce fixation durations.

## Study 2: Causal Attribute Biases

The results of study 1 demonstrate that variation in attention can account for a sizable fraction of the differences in discount rates, both within and across individuals. However, despite the evidence suggesting that a sizable fraction of the variation in attention is exogenous, the tests are purely correlational and cannot rule out the possibility that the direction of causality runs in the opposite direction. These later studies, as well as two studies reported in the online appendix, were designed to address this issue.

In study 2 (Figure 3), we manipulated the relative attention paid to different attributes and tested whether this altered the likelihood that participants made a patient choice. Here, participants faced trials where they were forced to attend to the different attributes for a particular amount of time before they were allowed to enter their response. Relative attention was manipulated within participants as each participant spent either more time fixating toward the monetary amounts or more time fixating toward the delays, depending on the trial. We manipulated exposure to

amounts versus dates because the results of study 1 suggest that this may affect patience, given the asymmetric impact of fixating on the earlier date and delayed monetary amount, versus the other features. By this logic, exogenously increasing the time spent fixating to amounts should increase patience while increasing the time spent fixating to dates should decrease patience.

## Task

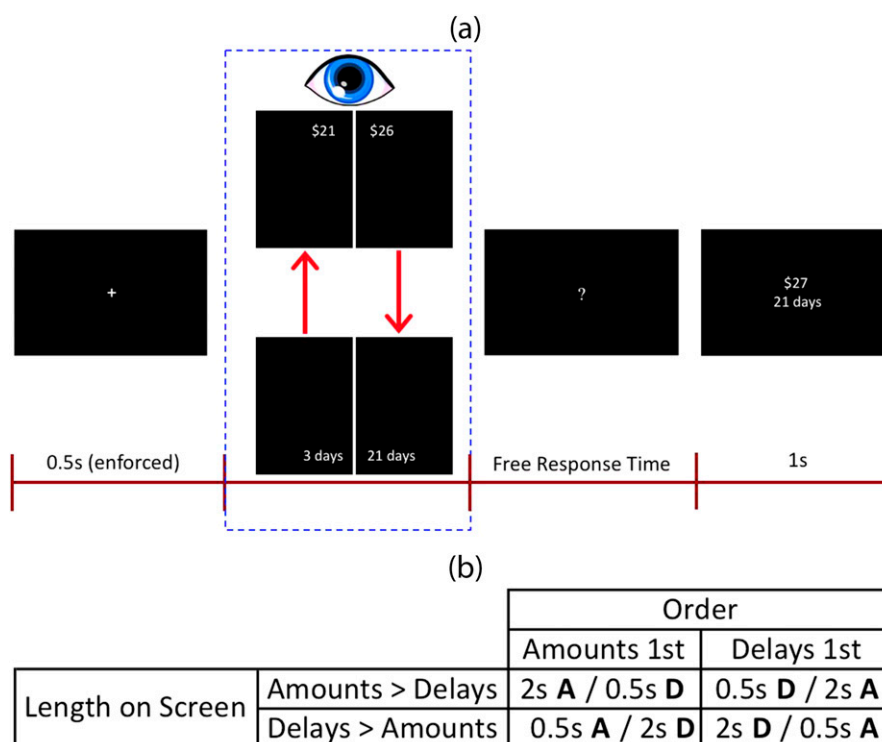
Thirty-six participants encountered each of 40 choice problems four times, in a random order, for a total of 160 trials. In each trial, participants first viewed a fixation cross at the center of the screen and were asked to fixate on it for 500 ms. The trial would only proceed once they had done so. Next, we exogenously varied visual attention to the amounts and dates by alternating between two display screens: one screen depicted only the amounts and the second depicted only the delays. In all screens, the two attributes were displayed next to each other in order to facilitate processing them in parallel. Each of the 40 questions appeared in all four conditions, which varied both the relative exposure to amounts and delays, as well as the order in which they appear. The length of the exposures was enforced by the eye tracker so that, for example, in trials in which amounts appeared for longer than delays, the screen would not advance until the participant had looked at amounts for a total of two seconds. Eye movements were monitored at 1,000 Hz, using a desktop mounted SR Research Eyelink 1000 Plus.

Every trial involved five seconds of enforced exposure, which allowed for two showings of each of the attributes, one for a total of four seconds and the other for a total of one second. Afterward, a question mark appeared, which cued participants to enter a response by key press, just as in study 1. After seeing feedback of their choice for one second, the task advanced to the next trial.

Participants were not informed that there were different types of trials and were allowed to take a short break every 25 trials. At the end of the task, the computer randomly selected a single trial that would be implemented. All payments were implemented as in study 1, and at the end of the experiment, participants completed a brief questionnaire, and responses are reported in the online appendix. The study lasted an average of 35 minutes (SD = 3 minutes), and the average total payment was \$30 (SD = \$10).

Several features of the experiment are worth highlighting. First, given the sizable individual variation in discount rates, we used a within-participants design to increase statistical power. Second, we manipulated exposure to amounts versus dates because the results of study 1 suggest that this may affect patience, given the

**Figure 3.** (Color online) Design for Study 2



**Notes.** (a) Trial structure for choice task in study 2. First, participants fixated on a central fixation cross for 500 ms. Next, they saw a pair of screens that alternated for a fixed length of time, depending on which of the four conditions was implemented. After switching between the two screens for a minimum of five seconds, participants were shown a question mark and had as long as they liked to enter a choice but could only enter their response once they saw the question mark. Afterward, feedback was shown for one second, and participants continued to the next trial. (b) Exposure structure for the four different conditions. Both the length that each screen appeared and its order were varied. Each experimental cell repeated itself in each trial so that the total exposure time was not less than five seconds and could last longer depending on when the participant fixated to the visible attributes.

asymmetric impact of fixating on the earlier date and delayed amount, versus the other features. Third, by manipulating the order of exposure, we control for the possibility of order effects. Fourth, we emphasize that exposure need not be exactly equal to attention in this task. For example, participants might have made a choice before the end of the exposure cycle and thus might not process the stimuli throughout the last part of the trial. Participants might also have been distracted by the need to detect screen changes and move their eyes in response. As a result, there is uncertainty about the size of the relative attention difference that is generated by the different conditions. Finally, it is possible that the sequential presentation of amounts and dates could prompt a different processing strategy (e.g., an attribute-based comparison process) compared with what would have been used if eye movements were free to vary, as in study 1. Notably, all participants in this study were restricted to such an information processing strategy, and hence, the study here investigates how exogenous variation in attention to the attributes under such a search strategy affects patience. Relevantly, analyses from study 1 suggest

different processing strategies do not yield large differences in the relationship between attention and choice.

## Results

We first examined the eye-tracking data to ensure the manipulation biased visual attention. By construction, participants spent four seconds fixating to monetary amounts and one second fixating to delays in trials when amounts were displayed for longer than delays. Likewise, they spent four seconds fixating to delays and one second fixating to amounts in trials when amounts were displayed for less than delays. We found that when attention was shifted to amounts, participants spent 2.1 seconds (SD = 0.3) fixating to the delayed monetary amount and only 0.4 (SD = 0.1) seconds fixating to the earlier date ( $t(35) = 28.43$ ,  $p < 0.001$ ); when attention was shifted to the delays, participants spent 1.8 seconds (SD = 0.1) fixating to the earlier date and only 0.5 seconds (SD = 0.0) fixating to the delayed monetary amount ( $t(35) = 28.43$ ,  $p < 0.001$ ). This suggests the manipulation successfully biased attention to the two features that were previously

identified in study 1 (i.e., the earlier date and the delayed monetary amount) as being highly correlated with choices.

We next carried out two separate analyses on the choice data. First, we compared choices in trials where amounts were displayed for longer than delays to choices in trials where delays were displayed for longer than amounts. In particular, we computed the number of patient choices and estimated the  $k$  discounting parameter separately for each participant and group of trials and compared them using two-sided paired  $t$  tests. We found that participants made 38.0 patient choices ( $SD = 24.4$ ) when amounts were displayed for longer than delays and 36.2 patient choices ( $SD = 24.5$ ) in the other case. This amounts to a 5% increase in the number of patient choices as the result of the exposure manipulation ( $t(35) = 3.68$ ,  $p < 0.001$ ;  $SD_{Diff} = 2.9$ ). A similar result was found when we examined at the estimated discount rates: the estimated  $\log(k)$  was  $-5.22$  when amounts are shown for longer than delays and  $-5.11$  otherwise ( $t(35) = 2.84$ ,  $p = 0.008$ ). The direction of these effects was consistent with the predictions made based on the findings of study 1. Results reported in the online appendix find the effect was stronger for those participants who displayed an intermediary level of patience, suggesting attention might have a larger impact for those who are closer to indifference.

Second, we carried out a similar analysis comparing the trials in which amounts were shown first to those trials in which delays appeared first. We did not find a significant order effect using either the percentage of patient choices ( $t(35) = 1.14$ ,  $p = 0.264$ ) or the estimated  $\log(k)$  ( $t(35) = 0.17$ ,  $p = 0.869$ ), indicating that total fixation time might play a larger role than order of fixations.

To examine how well the hyperbolic model fit the choice data, we estimated and used  $k$  from each condition to make a choice prediction for every trial. We found this procedure was consistent with observed choice in 91.1% ( $SD = 5.8\%$ ) of trials, suggesting the model accurately fits the data.

These results are consistent with the hypothesis that changes in relative attention to different attributes has a causal impact on the ability to make patient choices and suggests that some of the within and cross individual differences in discount rates, identified in study 1, are caused by attentional variation.

### Study 3: Causal Option Biases

Although study 2 found evidence that exogenously manipulating attention alters discounting, the effect was smaller than the correlational results in study 1 might suggest. One possible interpretation of the small effect size is that the relative deployment of attention is more endogenous than the previous literature

and results suggest. However, another possible interpretation is that carrying out meaningful manipulations of attention is difficult and that in the previous experiment, attention might not have varied as much across conditions as intended, perhaps because participants internally decided before the exposure time terminated.

Study 3 was designed to address this issue (Figure 4). Here, participants were free to fixate between the earlier and delayed outcomes, but once a specified accumulation time had been reached for an option, where one option might have a larger accumulation time than the other, it was removed from the computer screen. This still manipulates attention to certain features on the screen, but the intention was to create an environment where fixation and behavioral patterns more closely matched those in study 1.

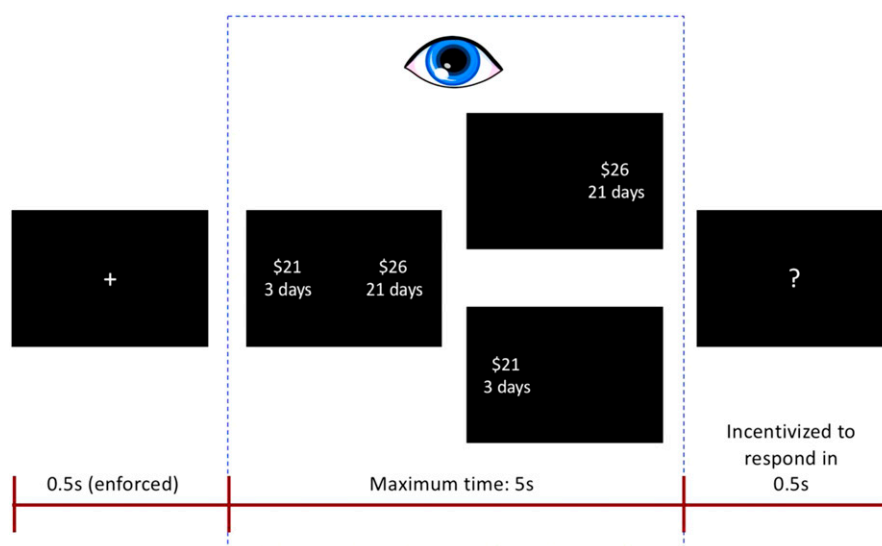
### Task

Thirty-one participants encountered each of 40 choice problems three times, in a random order, for a total of 120 trials. In each trial, participants first viewed a fixation cross at the center of the screen for 500 ms, which was enforced by the eye tracker. Next, the two choice options were displayed on the screen, and participants were free to look between them.

Unknown to the participants, in each trial, the computer selected either (a) one of the options to be the target and the other to be the nontarget or (b) both to be equal. Throughout the trial, the computer recorded the total duration that each option was attended to, and once an option reached its maximum fixation time, it disappeared from the screen. As one option must reach its maximum fixation time before the other, this resulted in having only one option visible on the screen after the other reached its maximum fixation time. Once both options reached their maximum fixation time, or a total of five seconds since the start of the trial elapsed, a question mark appeared at the center of the screen, and participants were instructed to indicate their response as quickly as possible. The maximum fixation time for the target option was 1.2 seconds, the maximum fixation time for the nontarget option was 0.3 seconds, and the maximum fixation time for equal options was 0.75 seconds. Each of the 40 choice trials appeared in three conditions: the earlier option was the target and the delayed was the nontarget, the delayed option was the target and the earlier was the nontarget, or both were equals. Importantly, participants were not informed that there were different types of trials.

In order to encourage participants to respond quickly on seeing the question mark, they were told that if in at least 100 of the 120 trials they responded within 0.5 seconds of the question mark appearing, they would receive an additional \$5 at the end of the experiment. No information regarding their response speed was provided at the time of choice. Eye movements were

**Figure 4.** (Color online) Trial Structure for the Choice Task in Study 3



*Notes.* First, participants fixated on a central fixation cross for 500 ms. Next, they saw both choice options presented and were free to fixate between them. One option was randomly designated the target, and the other was the nontarget, or both were equal. Once the target (nontarget) option was fixated at for 1.2 (0.3) seconds, it disappeared from the screen leaving only the nontarget (target) visible. Then, once the nontarget (target) option was attended to for a total of 0.3 (1.2) seconds, it also disappeared, and a question mark appeared in the center of the screen. This was the participant's cue to enter their response, and after doing so, feedback was shown, and they continued to the next trial. When both options were equal, the enforced fixation time for each option was 0.75 seconds.

monitored at 1,000 Hz using a desktop mounted SR Research Eyelink 1000 Plus.

Participants were allowed to take a break every 25 trials. At the end of the task, the computer randomly selected a trial that would be implemented. All payments were implemented as in the previous sections, and at the end of the experiment, participants completed a brief questionnaire with responses reported in the online appendix. The average total payment was \$33 (SD = \$6).

Two features of the experiment are worth highlighting. First, whereas study 2 found evidence that differential attention to amounts and delays could lead to choice biases, this experiment sought to test whether differential attention to the options could induce choice biases. It is possible that the presentation of options here could prompt a different processing strategy (e.g., an option-based comparison process) compared with what would have been used if eye movements were free to vary, as in study 1, or when attributes were displayed sequentially, as in study 2. Notably, all participants were presented with information in the same format so the study here investigates how exogenous variation in attention to the options affects patience. Furthermore, analyses from study 1 suggest different processing strategies do not yield large differences in the relationship between attention and choice, as noted earlier. Second, in this task the time from choice onset to decision

more closely approximated the time it would take to make a choice without any experimenter attention manipulation. Participants saw the options for a maximum total of 1.5 seconds and were incentivized to promptly enter their response afterward.

## Results

We first verified that the experimental manipulation successfully biased fixations toward the target option. Participants spent 1.19 seconds (SD = 0.02) fixating to the target option and 0.30 seconds (SD = 0.00) fixating to the nontarget option, indicating the manipulation was successful in altering relative attention, as measured by fixations.

Second, we compared behavior in this experiment to that in study 1. Here, participants made 2.8 fixations (SD = 0.38) between the choice options, meaning that they, on average, viewed an option more than once. Furthermore, participants first looked left on 74% (SD = 35%) of the trial and the average time spent on a trial before entering a response was 2.5 seconds (SD = 0.2). Only 2.1% of the trials terminated at the five-second mark. Moreover, the required stimulus viewing time of 1.5 seconds was similar to the stimulus viewing time from study 1 (mean = 1.6 seconds, SD = 0.6 seconds), although participants made less fixations between options here than in study 1 (mean = 3.7 fixations, SD = 1.0 fixations). These results indicate that certain behavioral outcomes, particularly



response times and stimulus viewing time, were similar to those in study 1 but that the number of fixations between options still differed.

We then compared choices in all trials across the various attentional conditions and found a causal effect: when the delayed option was the target, participants made 16.8 (SD = 14.4) patient decisions, but when the earlier option was the target, participants made 15.2 (SD = 14.2) patient decisions. This difference of 1.6 patient choices is significant ( $t(30) = 4.22, p < 0.001$ ), and the effect size indicates that the number of patient choices increased by 11%. A similar result was found when we examined the estimated discount rates: the estimated  $\log(k)$  was  $-5.00$  when the target was the delayed option and  $-4.75$  when the target was the earlier option ( $t(30) = 3.64, p = 0.001$ ). Results in the online appendix suggest the effect was stronger for those participants who displayed an intermediary level of patience.

Moreover, in a baseline condition when the options were attended to for an equal duration, participants made 16.2 (SD = 14.7) patient decisions, which suggests that drawing attention to the delayed option increased patience relative to a baseline ( $t(30) = 2.08, p = 0.046$ ) and that drawing attention to the earlier option decreased patience relative to a baseline ( $t(30) = 2.82, p = 0.009$ ). We found a similar result when we examined the estimated discount rates as the estimated  $\log(k)$  was  $-4.87$  in the baseline (baseline versus delayed option as target:  $t(30) = 2.85, p = 0.008$ ; baseline versus earlier option as target:  $t(30) = 1.90, p = 0.066$ ).

To examine how well the hyperbolic model fit the choice data, we estimated and used  $k$  from each condition to make a choice prediction for every trial. We found this procedure was consistent with observed choice in 90.6% (SD = 6.9%) of trials, suggesting the model accurately fits the data.

These results are consistent with the hypothesis that changes in relative attention to different choice options has a causal impact on the ability to make patient choices and suggests that some of the within- and cross-individual differences in discount rates, identified in study 1, are because of attentional variation.

#### Study 4: Causal Purchasing Decisions

Although studies 2 and 3 suggest that attention causally influences patience, these studies are limited in their stimuli to decisions over accepting money earlier or later. Although it is likely that these types of preferences are the building blocks of intertemporal consumer behavior and that participant responses to these questions are correlated with purchasing behaviors, study 4 sought to establish a clear link between purchasing habits over time and attentional deployment.

Moreover, studies 2 and 3 manipulate attention using a variety of short exposure times for particular choice features. Although previous work suggests consumers are both able to process information in these short time exposures and make accurate decisions in relatively short durations (Milosavljevic et al. 2011), the results above cannot rule out the explanation that participants were unable to process all the decision-relevant information. To resolve this, study 4 tested participants' perception of the stimuli by asking them to make binary choices between possible choice sets. A more thorough test for this appears in an additional study reported in the online appendix and finds that participants were equally able to recall feature values from a choice set regardless of the fixation timing used at a success rate of approximately 90%.

#### Methods

Twenty-seven participants made decisions over when they would prefer to purchase several types of consumer goods (Figure A2 in the online appendix). Participants decided whether they would prefer to purchase a laptop computer, tablet computer, or pair of headphones either today or in a number of months when they were offered for less money. Participants were instructed to imagine a situation in which they had an older version of the good and were interested in purchasing the latest model that was recently introduced. They could charge the full amount to a credit card, but they knew that the price would decrease over the next several months. Participants were paid \$20 for their participation, but none of the purchase decisions were enforced.

The experimental design was similar to study 2. Participants answered 40 trials over three goods in a randomized order for a total of 120 decisions. Every 25 trials, they were instructed they could take a break. Participants encountered each purchase problem four times in random order. Exposure time to the attributes, either purchase amounts or delays, was manipulated in a similar way to study 2.<sup>5</sup> Every trial involved 3.8 seconds of enforced exposure, which allowed for two showings of each of the attributes: one for a total of 3 seconds and the other for a total of 0.8 seconds. Laptops were always offered with one option to purchase at \$2,000 today, tablets at \$600 today, and headphones at \$350 today, all with declining prices over the next several months. Stimulus values and choice probabilities are reported in Table A25 of the online appendix, and we opted to use the word *today* as an immediate delay to increase the realism of the choice frame. Eye movements were recorded at 1,000 Hz using an SR Research Eyelink 1000 Plus desktop-mounted eye tracker. Participants were given a questionnaire with the open-ended

question “what do you believe this study is about?” No participant made any reference to changes in attention across trials or that different trials had different fixations lengths for prices or delays.

Five times throughout the experiment, participants did not see the feedback screen for their choice. Instead, they were shown two different choice sets. One choice set included the shorter duration attributes that appeared in the previous trial, and the second included “dummy” shorter duration attributes. Participants were asked to select which choice set they made a decision over in the previous trial. As one option for every decision was always offered both today and at the same price for each good, these *dummy* questions only altered the shorter duration attribute of the future option. For example, if deciding between purchasing a laptop for \$2,000 today or \$1,750 in three months and having the prices appear for less time than the delays, participants might be shown the options of “\$2,000 today or \$1,750 in 3 months” and “\$2,000 today or \$1,800 in 3 months” and asked to decide which option they just decided between. The dummy attribute was randomly chosen from the set of all future attributes displayed for that particular product. These questions were designed to verify that participants could correctly process the short duration attributes they were exposed to, although online appendix study 1 presents a more complete test of this hypothesis.

## Results

We first examined the eye-tracking data to ensure the manipulation biased visual attention. By construction, participants spent 3 seconds fixating to prices and 0.8 seconds fixating to delays in trials when amounts were displayed for longer than delays. Additionally, we found that when attention was shifted to prices, participants spent 1.6 seconds ( $SD = 0.2$ ) fixating to the more desirable lower price and only 0.3 ( $SD = 0.1$ ) seconds fixating to the earlier date ( $t(26) = 26.04, p < 0.001$ ); likewise, when attention was shifted to the delays, participants spent 1.3 seconds ( $SD = 0.1$ ) fixating to the earlier date and only 0.4 seconds ( $SD = 0.0$ ) fixating to the lower price ( $t(26) = 21.03, p < 0.001$ ). Overall, this suggests the manipulation successfully biased attention to the two features that were previously identified in study 1 as being correlated with choices.

Next, we compared choices in trials where prices were displayed for longer than delays to choices in trials where delays were displayed for longer than prices. We found that participants made 34.1 patient decisions ( $SD = 13.5$ ) when exposure to prices was longer than delays and 31.8 patient decisions ( $SD = 13.3$ ) when exposure to delays was longer than to prices ( $t(26) = 3.33, p = 0.003$ ). This amounts to an approximately 7% increase in the number of patient

decisions. We found that, on average, as attention was shifted to the prices, participants were willing to wait an additional 0.3 months to purchase an item.

Second, we carried out a similar analysis that compared the trials in which the prices were shown first to those in which the delays appeared first. As in study 2, we did not find a significant order effect on the number of overall patient choices made across the three goods ( $t(26) = 1.42, p = 0.167$ ).

Finally, we tested whether participants were able to properly process the short-duration stimuli. Across each participants' five test questions, 96% of the true choice sets were correctly chosen. This indicates that participants were able to process and remember the stimuli they recently made decisions over, even when the attributes were only fixated to for short durations. This is notable because, although these questions included trials in which the participant chose to purchase the good immediately, participants were still able to accurately remember the option they did not choose, which was the only option varied between in the choice set questions.

Overall, the results here are consistent with the hypothesis that changes in relative attention to different attributes has a causal impact on the ability to make patient choices and extend the previous results to consumer purchasing.

## Discussion

This paper describes the results of four studies (and two in the online appendix) designed to test whether exogenous fluctuations in the relative attention paid to different features during intertemporal choices can influence the ability to delay gratification. Consistent with this hypothesis, we found shifting attention toward the delayed monetary amount was associated with a sizable increase in the likelihood of making a patient choice, whereas shifting attention toward the earlier date had a sizable effect in the opposite direction. Furthermore, between 40% and 53% of individual differences in discount rates could be explained by individual differences in the average relative propensity to look at different features. Interestingly, we found that the within and between participant results were consistent with one another: in both cases the attentional variable that had the largest impact in explaining variation in patience was the propensity to shift attention to the earlier date, followed by the propensity to look at the delayed amount.

A critical question underlying the results is the direction of causality between the fluctuations of attention and the decision-making processes. One set of models that motivate this paper assumes observed fluctuations in attention are not driven by the state of the relative value signal that drives choice. If this is correct, the results from study 1 would suggest that a

sizable fraction of the within and cross participant variation in discount rates is driven by fluctuations in attention. However, it is also possible to write simple variations of these models in which the state of the relative value signal influences the deployment of attention toward attributes that are *consistent* with the attributes and option favored at that instant. Understanding how much of this variation can be causally attributed to attention is critical to evaluate the implications of this work. The analysis of the fixation data at the end of the study 1 results suggests there might be an influence from the choice process to the deployment of attention; however, the effect appears small in this case, especially compared with previously observed value-related biases. The results of studies 2–4 and the two studies reported in the online appendix, in which attention was manipulated exogenously, suggest that there is a causal effect from attention to intertemporal choice.

Given the sizable differences in exposure time in study 2, the relatively small overall effect size is surprising. There are several potential explanations for this finding. First, it is possible that the direction of influence from fixations to choices runs in both directions and that a sizable fraction of the correlations identified in study 1 is caused by an influence of perceived value on attention. Second, the experimental manipulation might have had a small impact on the actual relative processing of the attributes, because participants may have made their decisions before the exposure was completed, which would lead to a reduced impact on choices. Disentangling these hypotheses is challenging, as it requires measuring the *latent* state of the choice process before a response is made and to measure processing time by the decision-making circuitry without using fixations. Third, the task parameters were not optimized to generate the maximum possible effect; it is possible a different manipulation could have led to a more sizable effect. Notably, we do find a substantially larger effect among those participants who displayed an intermediary level of patient behavior. Additionally, studies 3 and 4 find evidence that a larger effect can occur. Given the differences between the causal studies, it is difficult to precisely pinpoint why the effect size differs. For instance, it may be related to testing for an option versus attribute bias, differences in exposure time, differences in the choice response process, or differences in the task stimuli (e.g., purchasing goods versus monetary decision making). It is possible that altering any of these parameters of the experiment can lead to even larger effect sizes than those observed here.

The study here builds on and contributes to several types of literature. First, the results build on a pioneering set of papers that have used attentional measures to test algorithmic models of how preferences are constructed and compared at the time of decision (Russo and Rosen 1975, Russo and Doshier 1983, Johnson et al. 2008, Willemsen et al. 2011). The association between attention and contextual effects has also been used to explain preference reversals (Busemeyer and Townsend 1993, Roe et al. 2001, Kim et al. 2012) and context effects in risky choice (Johnson and Schkade 1989, Willemsen et al. 2011). Our contribution to this existing work is to show that these ideas extend to the domain of intertemporal choice and that attentional variation could potentially be a critical variable in explaining differences in the ability to delay gratification across individuals and contexts. An important direction for future research in this area is to carry out experiments that allow for more quantitative model fitting and testing, including a formal comparison of the various types of attentional biases that have been proposed by different types of models. This could not be done with the current design, as it requires decorrelating the different attributes and a larger number of trials.

Second, the results build on a large body of work that has shown that individuals exhibit hyperbolic discounting in intertemporal choice, which can lead to difficulties in delaying gratification when one of the options entail an immediate reward (Madden et al. 1997, Frederick et al. 2002, Kable and Glimcher 2007, Chabris et al. 2008). One critical finding in this literature is that discount rates are not constant and instead decrease with distance to the present. The results of study 1 show that shifts in attention toward the immediate delay attribute had an especially strong impact on discount rates. This suggests that some of the *hyperbolicity* of the discount function might be attributable to attentional effects and might be more sensitive to training and context than *deeper* preference parameters.

Third, the results have implications for how to design interventions that could increase an individual's ability to postpone gratification. In particular, they suggest that any contextual variable, or nudge, that directs attention toward the long-term benefits of self-control, and away from the immediate rewards, might improve self-control. Additional evidence consistent with this comes from studies have found that changes in the low-level visual features of stimuli can affect the relative attention they receive, and through it, the likelihood that they are selected (Milosavljevic et al. 2012, Towal et al. 2013). A systematic investigation of



these possibilities in the domain of intertemporal choice is an important open question for future research.

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## Endnotes

<sup>1</sup> In certain analyses entailing the estimates of  $k$ , we choose to analyze the logarithm of  $k$  rather than  $k$  itself. We do this as a result of the functional form of the hyperbolic discounting model. When  $k$  is relatively low, small changes in  $k$  can produce large changes in decisions; yet when  $k$  is large, the same size changes will produce less noticeable decision alterations.

<sup>2</sup> Several pieces of evidence support this comment. First, as there are no restrictions on where one should fixate throughout the task, any covertly attended features can be easily fixated. In fact, Posner et al. (1984) find that covertly attending to a piece of information is soon followed by a saccade to that information. Second, in some instances eye fixations can be so inexpensive for the decision maker that fixations substitute for the use of working memory as a storage and retrieval system (Droll and Hayoe 2007). Third, many of the models that motivate our hypothesis allow evidence accumulation to depend on the value of all features in the choice set but find that the rate of accumulation is biased toward the currently fixated information.

<sup>3</sup> If participants tend to use attribute-based or option-based models in an equal proportion, then pooling all participants in a single analysis could maintain the impact of the delayed amount and earlier date but eliminate the mixed result of the earlier amount and later date. To address this, the online appendix reports an analysis that classifies participants based on their search strategies. Although the data identify two distinct search strategies, there is not a large difference between the two in how attention to features is correlated with patience. Although some evidence suggests that search strategy is correlated with choice (as in Reeck et al. 2017), controlling for search strategy and attention to the features correlated with choice all jointly influenced patience.

<sup>4</sup> It is relevant to emphasize certain limitations of this test. First, the types of models with attentional biases that inspire the analysis predict a correlation between the trial's attribute values and the relative fixation statistics, even when attention is fully exogenous. The reason for this is that attentional biases make it more likely that the last fixation is to an ROI that favors the chosen option. However, because the magnitude of such a correlation depends on the parameters of the model, the current experiment does not allow a method to determine what fraction of the observed correlations in Table 5 are consistent with this possibility. Second, the test assumes a linear relationship between attention and feature values, and certain transformations of feature values might alter the reported effect size.

<sup>5</sup> Hence, it is possible that the sequential presentation of amounts and dates could prompt a different processing strategy (e.g., an attribute-based comparison process) compared with what would have been used if eye movements were free to vary, as in study 1. Notably, all participants in this study were restricted to such an information processing strategy, and hence, the study here investigates how exogenous variation in attention to the attributes affects patience in a simple purchasing task.

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