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Exploring the decision dynamics of risky intertemporal choice

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Abstract

Previous research on the effects of probability and delay on decision-making has focused on examining each dimension separately, and hence little is known about when these dimensions are combined into a single choice option. Importantly, we know little about the psychological processes underlying choice behavior with rewards that are both delayed and probabilistic. Using a process-tracing experimental design, we monitored information acquisition patterns and processing strategies. We found that probability and delay are processed sequentially and evaluations of risky delayed prospects are dependent on the sequence of information acquisition. Among choice strategies, directly comparing the values of each dimension (i.e., dimension-wise processing) appears to be most favored by participants. Our results provide insights into the psychological plausibility of existing computational models and make suggestions for the development of a process model for risky intertemporal choice.

Keywords: Risky Intertemporal Choice; Process Tracing; Path Dependency; Sequential Processing; Decision Strategies

Introduction

While research on risky choice and intertemporal choice have separately provided significant insights into the effects of probability and delay, decisions which involve both elements have received less scrutiny. Two unresolved questions are whether probability and delay are processed sequentially (and if yes, which dimension is considered first), and whether evaluation of risky delayed prospects is path dependent. Öncüler and Onay (2009) found that the order in which participants processed risky delayed prospects affected the final evaluations of these prospects. Using a process-tracing design, they found that amount-related (i.e., money) information was acquired first most often, followed by information about delay and then probability. Interestingly, when participants were required to process delay first, they provided higher evaluations of the same prospect compared to when they processed probability first, supporting the view of path dependency in risky intertemporal choice.

Despite being central to the characterization of choice behavior, no other studies have utilized process-tracing methods in the domain of risky intertemporal choice. Process-tracing methods can provide insightful observations about the processes that take place before the actual decision, such as search, integration, and processing of available information (e.g., Reisen, Hoffrage, & Mast, 2008). In risky intertemporal choice they can provide information about the order in which participants integrate amount, delay, and probability information as well as choice strategies adopted. Accordingly, process data can set the foundations for the development of computational models and offer testable predictions regarding the choice process.

The experimental results relating to path dependency and sequential evaluation are not readily explained by traditional expected discounted utility models. These models focus on predicting choice outcomes (*descriptive as-if* models), hence arguably not accounting for the underlying psychological processes that are responsible for choice behavior, or simplifying strategies (e.g., heuristics) that people may employ in their decision-making. For instance, some expected utility models assume that people integrate probability and delay information into a common metric of psychological distance (e.g., Baucells & Heukamp, 2012; Vanderveldt, Green, & Myerson, 2015). However, Öncüler and Onay (2009) observed in their process data that this strategy was not favored (i.e., transitions between probability and delay information were the least frequent), thus rendering the "common psychological distance" account less likely among competing explanations.

The main purpose of the current work is to extend Öncüler and Onay's (2009) investigation from a pricing task, in which participants had to indicate the present certainty equivalent or pCE of a risky delayed prospect (the minimum amount of money that one is willing to accept instead of a delayed gamble) to a choice task in which participants choose between two risky delayed prospects. We then examine the predictions for path dependency and sequential evaluation in both tasks. This comparison allows us to ask whether choice is also characterized by path dependency and whether the characteristics of this dependency are similar between choice and pricing. The identification of such characteristics and processing strategies can also inform the development of models that rely on psychologically plausible accounts of choice behavior (i.e., psychological process models). Such models have become increasingly popular in many areas of decision-making (e.g., Koop & Johnson, 2013), and often assume that decision-making follows simple rules of information processing, such as dimension-wise evaluation, sequential processing, and partial integration of available information (see e.g., Brandstätter, Gigerenzer, & Hertwig, 2006).

Method

Participants

We tested a total of 63 undergraduate students (42 female; Age: $M = 19.02$, $SD = 1.56$) at the University of New South Wales who participated in return for course credit.

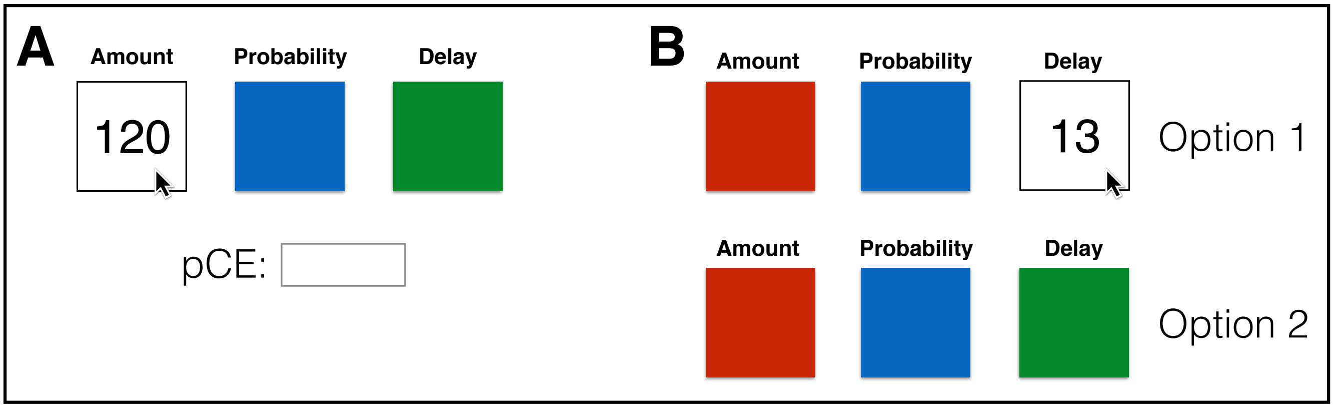

Figure 1: Schematic representation of the experimental design in the pricing (A) and choice (B) tasks. In the pricing task, participants could open as many boxes as they wanted before they gave the pCE of the delayed lottery. There was no limit about the time inspecting a box. The position of each dimension on the screen (Amount, Probability, and Delay) was randomized across trials. The association between colored boxes and dimensions remained invariant throughout each experimental session but was randomized across participants. The design was identical in the choice task and participants had to choose between two delayed lotteries. In this screenshot, the mouse opens an Amount box in the pricing task (i.e., \$120) and a Delay box of Option 1 in the choice task (i.e., 13 months).

Task and design

We used a process-tracing design (i.e., similar to a MouseLab information board; see Payne, Bettman, & Johnson, 1993) to monitor information acquisition strategies and processing steps. The experiment consisted of two parts: the first part was a *pricing* task, where participants had to indicate the pCE of 68 delayed lotteries (presented sequentially and in random order). For each delayed lottery, there were 3 colored boxes in the center of the screen, each containing the numerical value of each lottery's dimensions: Amount of money (in \$), Probability (in %), and Delay (in months; see Figure 1A). However, this information was hidden and revealed only upon clicking on each corresponding box. When participants clicked on a box, it stayed active (i.e., showing its value) as long as the mouse cursor was within the borders of the box. When they moved the mouse out of the box, it returned to its default state (i.e., hidden). There was no limit in the amount of clicks or the time inspecting a box. In addition, participants could return to an already seen box if they wanted to. The position of each box was randomized across trials.

The second part was a *choice* task (Figure 1B), which always followed the pricing task and involved a choice between two delayed lotteries. Unbeknownst to the participants, the choice dyads were formed using pairs of prospects from the pricing task (34 choice pairs from 68 delayed lotteries). The procedure of acquiring information about each delayed lottery was identical to the pricing task.

Procedure

Participants sat in front of a computer screen and were given instructions about the task (e.g., details about the information acquisition in the pricing task and what pCE represents). There was also a practice stage prior to the main task where participants could familiarize themselves with the process-tracing character of the task. For the pricing task, there was a box where they could type in their evaluation (Figure 1A). For the choice task, they were told that the task is exactly the same as before, with the only differences being that there was an extra option on the screen and they had to choose between the two, by clicking on the corresponding option label (Figure 1B).

Results

Pricing Task

All participants completed the experiment. We excluded one participant because they never acquired probability and delay-related information. Our initial objective was to explore the basic properties of information acquisition in the pricing task (see Figure 2): the frequency that each dimension was inspected, the frequency that each dimension was inspected first (i.e., at the beginning of each trial), last (i.e., before participants provided the pCE value), and intermediate (i.e., excluding first and last inspection items), and the mean inspection time for each dimension. For the analysis of frequency data, we used a linear multilevel model with dimension as fixed-effect and random intercepts for each participant. We applied a square root transformation for the frequency data.[1] As Figure 2A suggests, participants acquired more amount-related information, followed by probability and delay, and this pattern was present in all categories of interest (All: $\chi^2(2) = 269.07, p < .001$; First: $\chi^2(2) = 60.67, p < .001$; Intermediate: $\chi^2(2) = 77.69, p < .001$; Last:

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[1] This analysis is equivalent to a chi-squared test of independence, but it accounts for individual heterogeneity in the data (see Willemsen & Johnson, 2011).

$\chi^2(2) = 96.18, p < .001$).[2] The same pattern is observed in the mean inspection time (Figure 2B): participants spent more time looking at amount information, followed by probability and delay ($\chi^2(2) = 67.20, p < .001$; significant differences between each dimension). Also, the relative preference for inspecting each dimension does not seem to change over time as can be seen in Figure 2C: block × dimension interaction, $\chi^2(6) = 1.19, p = 0.98$.

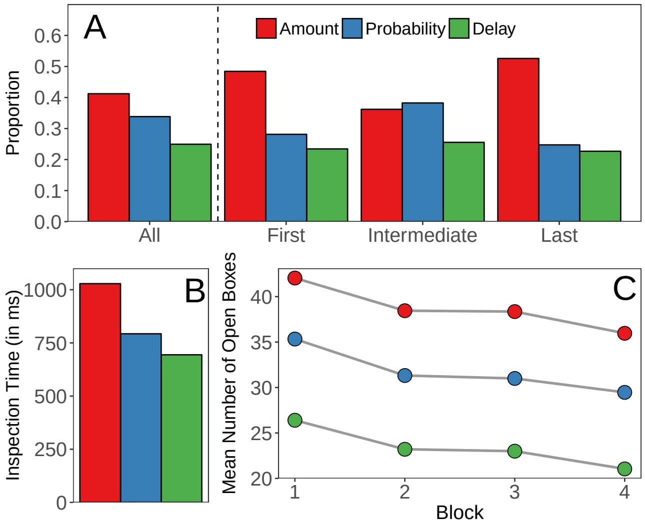

Figure 2: Graphical representation of information acquisition in the *pricing* task: A) Relative frequencies of opened boxes of each dimension (All: Overall; First & Last: First and Last boxes opened in a trial; Intermediate: Excluding First and Last boxes). B) Mean inspection time for each dimension. C) Pattern of acquisition items across blocks of trials (17 trials/lotteries each).

The next step in our analysis was to inspect transitions between consecutive ($n \leftrightarrow n+1$) information items. This analysis can provide us with information about the sequential nature of risky intertemporal choice. For example, based on the *adjacency* principle ("information used in temporal proximity should be acquired in close proximity"; see Johnson, Schulte-Mecklenbeck, & Willemsen, 2008, p. 264), if the Amount ↔ Probability transition occurs more often and temporally precedes the Amount ↔ Delay transition, it means that participants pay more attention to the amount and probability aspects of the prospect and probability discounting (or processing of probability) occurs prior to delay discounting (or processing of delay). Table 1 suggests that the Amount ↔ Probability transition not only occurs more often than any other transition (*All* column), but it seems to precede any other transition (*First* column), and be considered more often before the final evaluation of the lottery (*Last* column). The relatively low proportion of Delay ↔ Probability transitions suggests that participants are not attempting to create a common metric of psychological distance by integrating these two dimensions (cf. Öncüler & Onay, 2009).

Table 1: Transitions between dimensions in Experiment 1. The ↔ symbol indicates all transitions from one dimension to the other.

Transition	All: *N*	All: %	First: %	Last: %
Amount ↔ Probability	8,834	0.46	0.47	0.50
Delay ↔ Amount	5,117	0.27	0.28	0.27
Delay ↔ Probability	4,335	0.23	0.22	0.19

Note: Relative frequencies do not add up to 1 because transitions between the same dimension (e.g., Amount ↔ Amount) are not included in the table.

We then explored the concept of path dependency as suggested by Öncüler and Onay (2009) by comparing the final evaluations of lotteries when Amount ↔ Probability or Amount ↔ Delay was the first occurring transition. Öncüler and Onay found that when participants followed the Amount ↔ Delay path they gave higher evaluations of the same prospect compared to the Amount ↔ Probability path. Our results replicate this effect: when examination of delay preceded that of probability, participants gave higher evaluations for the majority of trials (70%). However, it is not clear how subsequent transitions in our experiment might have affected the final evaluation of the prospect. We try to address this issue along with the issue of imbalance in transitions (which emerges due to the higher frequency of Amount ↔ Probability transitions) in a following experiment.

Choice Task

Figure 3 presents information acquisition for each dimension in the choice task, aggregated across the two choice options. The pattern of results looks similar to the pricing task with a few exceptions: First, looking at the overall trend of dimension inspection, there is no difference between amount and probability (Figure 3A; $b = -0.01, t = -0.84, p = .40$), but both differ with respect to delay (pairwise contrasts, $p < .001$). A similar pattern is observed in the intermediate inspection items (no difference between amount and probability, $b = 0.07, t = 0.34, p = .73$, but they both differ from delay, $p < .001$). This presents a difference between the two methods of preference elicitation, indicating that in a choice setting amount and probability may have the same degree of influence on choice. As in the pricing task, the first dimension considered followed the amount > probability > delay scheme, $\chi^2(2) = 37.23, p < .001$, but there was no difference between dimensions regarding the last information item, $\chi^2(2) = 2.68, p = .26$. The mean time spent at each dimension (Figure 3B) was not different between amount and probability ($p = .95$), but both were higher than delay ($p < .001$). Regarding selection of each dimension across time, Figure 3C suggests that it does not change between the two halves of the choice task, $\chi^2(2) = 2.67, p < .001$.

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[2] All pairwise contrasts were significant, $p < .05$, apart from the contrast between probability and delay regarding the last item, and the contrast between amount and probability regarding intermediate items.

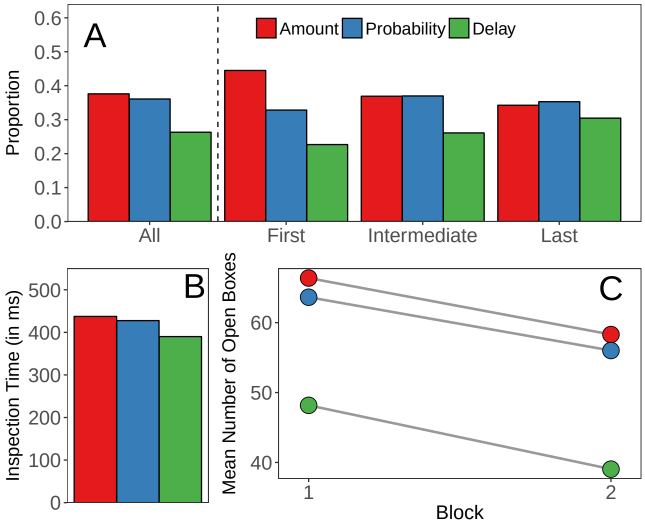

Figure 3: Graphical representation of information acquisition in the *choice* task, aggregated across the two options: A) Relative frequencies of opened boxes of each dimension (All: Overall; First & Last: First and Last boxes opened in a trial; Intermediate: Excluding first and last). B) Mean inspection time for each dimension. C) Pattern of acquisition items across blocks of trials (17 trials/choices each).

Next, we examined transitions between consecutive information items ($n \leftrightarrow n+1$) which are informative of the strategies that participants use. Assuming a 2×3 information board/grid where rows represent *choice alternatives* and columns *dimensions* (as in Figure 1B), transitions between items can be categorized as *dimension-wise* (or intradimensional: when the transition examines the same dimension between the two choice options, e.g., Amount in Option 1 ↔ Amount in Option 2), *alternative-wise* (or interdimensional: when the transition moves between different dimensions of the same option, e.g., Amount in Option 1 ↔ Delay in Option 1), *diagonal* (i.e., when the transition moves from one dimension of one option to a different dimension of the other option, e.g., Probability in Option 2 ↔ Delay in Option 1), and *same* (i.e., two consecutive inspections of the same dimension in the same option, e.g., Probability in Option 1 ↔ Probability in Option 1). Table 2 presents the frequency of each of the categories of transitions in the choice task: a first inspection of all transitions (*All* column) suggests that participants equally combined dimension and alternative-wise strategies. One of the most commonly used *strategy indices* (SI; Payne, 1976) suggests that participants equally used both strategies to make decisions. The SI is a ratio of the difference between alternative and dimension-wise transitions and it is defined as $\mathrm{SI} = (r_a - r_d)/(r_a + r_d)$, where r_a is the total number of alternative-wise transitions and r_d is the total number of dimension-wise transitions. It ranges between -1 to $+1$, with negative numbers suggesting more dimension-wise processing and positive numbers suggesting more alternative-wise processing. For our data, the *SI* equaled 0.06, indicating roughly equal use of both strategies.

Table 2: Categories of transitions in the choice task. Arrows indicate the direction of the transition within the information board (see Figure 1B).

Transition		All: *N*	All: %	First: %	Last: %
Dimension	↑↓	7,115	0.39	0.58	0.54
Alternative	⇄	8,072	0.44	0.39	0.39
Diagonal	⤢	3,117	0.17	0	0.07
Same	–	146	0.01	0.02	0.01

However, Böckenholt and Hynan (1994) argued that the SI is a biased measure of strategy use when there is a different number of alternatives and dimensions. Specifically, if the number of dimensions is larger than the number of the alternatives[3], then a positive SI is to be expected, indicating more alternative-wise processing. Böckenholt and Hynan developed an index (*strategy measure*; *SM*) which takes into account all possible transitions (e.g., including Diagonal and Same in Table 2):

$$SM = \frac{\sqrt{N}[(\frac{AD}{N})(r_a - r_d) - (D - A)]}{\sqrt{A^2(D-1) + D^2(A-1)}} \tag{1}$$

where N is the total number of all types of transitions, A is the number of alternatives, D is the number of dimensions, and r_a and r_d denote frequency for alternative-wise and dimension-wise transitions, respectively. As with the SI, negative values of the SM indicate more dimension-wise processing, as can be seen in Figure 4. Specifically, dimension-wise processing becomes more prevalent as time progresses, as indicated by the linear decrease of the *SM* value.

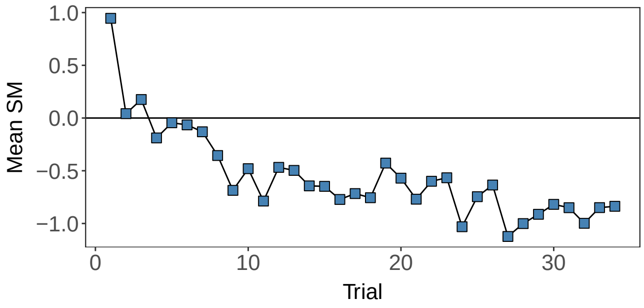

Figure 4: Strategy measure (*SM*) averaged across participants for each trial/choice of the task.

Experiment 1B: Constrained sequential search

Method The purpose of this experiment was to examine in detail the effect of path dependency observed in the pricing task. Participants ($N = 40$, $M_{age} = 19.08$) provided the pCE of risky delayed prospects sequentially (i.e., in two stages;

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[3] This is the case in our experiment. In fact, it is twice as likely for an alternative-wise transition to occur (6 transitions) compared to a dimension-wise (3 transitions).

see also upper panel in Figure 6): in the first stage, they could see either probability or delay (amount was always visible on the screen), and give the present value of the prospect (if delay was presented first), or the certainty equivalent value (if probability was presented first). The value they provided in the first stage appeared in the second stage along with the numerical value of the unseen dimension, and participants had to provide a second and final value for the prospect. We manipulated (three experimental parts) the way that participants acquired probability and delay-related information: a) a *free search* part where participants could select to see either probability or delay in the first stage, and b) two *constrained search* parts where either probability or delay was presented to participants first. Hence, participants were presented with the same risky delayed prospect three times.

Results We first examined search patterns in the free search part of the experiment: we found that in 68.50% of all trials, participants chose to see probability first, replicating the effect we observed in the pricing and choice tasks, that is a preference for inspecting and integrating probability information before delay information. We also examined search patterns as a function of the amount offered (amount was always visible on the screen). Figure 5 presents an interesting pattern: participants' tendency to inspect the probability dimension first increases as amount increases. Despite the overall preference for acquiring probability first (even in the lowest amount category, [50, 175), it is 64.38%) the difference between the lowest and highest amount categories is about 10% (74.16% in the last category).

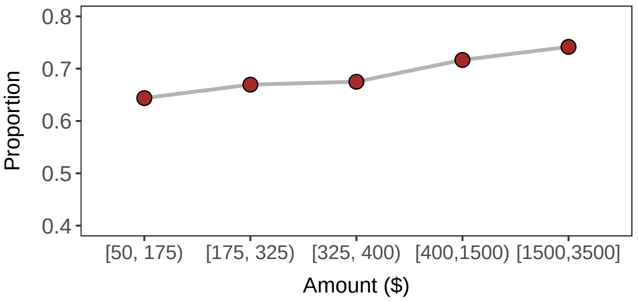

Figure 5: Proportion of trials in which participants chose to see probability first as a function of Amount (in $; binned in five equal categories).

Regarding path dependency, we examined the final pCEs in the constrained search parts of the task. Figure 6 shows the proportion of participants that gave a higher final evaluation when they were constrained to inspect probability first (as compared to delay first) as a function of the numerical values of each gamble's probability (lower panel A) and delay (lower panel B). For example, the leftmost data-point in Figure 6A indicates that for the same risky delayed prospect (which has a probability of 2%) about 40% of all participants gave a higher final pCE when they were presented with probability information first than when they were presented with delay information first (see also the table in the upper panel). Even though Figure 6 essentially ignores interactions between each dimension and collapses across all amount, probability, and delay values, it shows some interesting patterns. First, as the probability in a prospect increases, the proportion of participants who gave a higher evaluation when they were presented with probability first increases, as shown by a multilevel logit regression with probability as fixed effect and participant-specific random intercepts (standardized $b = 0.40, z = 4.44, p < .001$). Second, there is a similar trend in the delay panel (as temporal distance increases, the proportion of participants that gave a higher evaluation of the same gamble when they were presented with probability first increases) but it is not as pronounced as in the probability panel (standardized $b = 0.24, z = 2.70, p = .007$). Interestingly, this pattern seems to apply to small values of probability and delay, as when we constrain our analysis in the upper half of both scales (i.e., 50% to 90% for probability; 16 to 24 months for delay) the effect disappears (both multilevel logit regressions, $p > .05$). Overall, our results replicate the path dependency patterns in Öncüler and Onay (2009) and suggest that path dependency is not stable, but is moderated by the numerical values of each dimension.

	Probability First				Delay First		
Stage 1	\$450	2 % →	X_{PF}		\$450	21 M →	X_{DF}
Stage 2	X_{PF}	21 M →	Y_{PF}	>	X_{DF}	2 % →	Y_{DF}

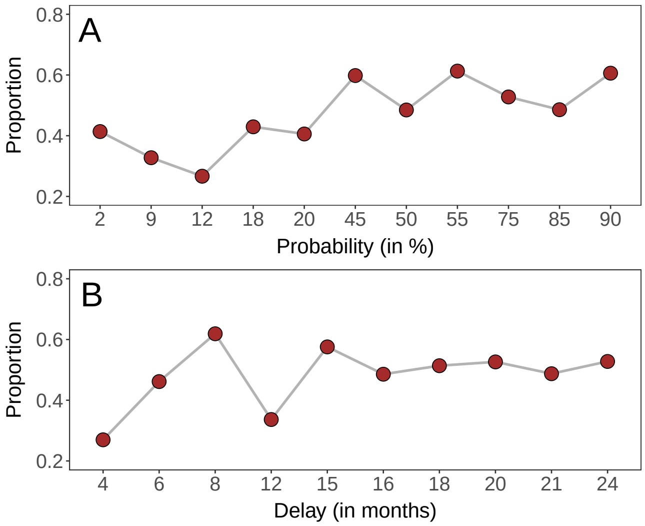

Figure 6: Upper panel: Representation of the task (M: Months). Lower panel: Proportion of participants who gave a higher final pCE (i.e., $Y_{PF} > Y_{DF}$) for the same gamble when they were presented with information about probability first across Probability (A) and Delay levels (B).

Discussion

We set out to uncover the strategies and information acquisition patterns that people use when they evaluate and make decisions about risky delayed prospects. Using three different process-tracing tasks to elicit preferences, we observed systematic patterns relating to search, integration, processing, and strategy-use. First, participants acquired more amount-related information, followed by probability and delay in the pricing task, whereas in the choice task amount and probability appeared to have the same degree of influence on determining choice. Our results are in accordance with recent studies in intertemporal risky choice which found that probability might play a more important role than delay (e.g., Konstantinidis, van Ravenzwaaij, Güney, & Newell, 2017; Vanderveldt et al., 2015), but are at odds with Öncüler and Onay (2009) who found that participants preferred to acquire delay information before and more frequently than probability information.

Second, Amount ↔ Probability transitions were more frequent and preceded any other transition in the pricing task. This pattern of results suggests that evaluation of risky delayed prospects is subject to sequential processing. Also, the integration of probability and delay into a common psychological distance measure seems less likely as the Probability ↔ Delay transition occurs less frequently and temporally follows other types of transitions.

Third, regarding path dependency and sequential processing, our constrained search experiment revealed that the final evaluation of risky delayed prospects is not only dependent on the path taken (i.e., integrating probability information before delay information, and vice-versa), but on the numerical values of each dimension. For example, when participants were first presented with low probability values, they largely discounted the final value of the same prospect as compared to when they saw delay-related information first about the same prospect. We found that the effect of path dependency observed in Öncüler and Onay (2009), that is, the Delay → Probability path generating higher values than the Probability → Delay path, is only observed with small probabilities.

Fourth, examination of transitions in the choice task reveals that participants employ dimension-wise strategies more frequently than alternative-wise strategies to make decisions in risky intertemporal choice settings. Even though there was no reliable difference between dimension and alternative-wise processing regarding the total number of transitions, taking into account different measures of strategy use (e.g., search indices, overall, first and last inspection items, and transitions between items), we found that dimension-wise processing may be more prevalent among participants, supporting recent studies which found that dimension-wise models in the domains of risky choice and intertemporal choice outperform their alternative-wise counterparts (e.g., Dai & Busemeyer, 2014).

Lastly, even though individual information acquisition patterns might reflect noisy and idiosyncratic use of strategies, we identified systematic processing strategies and information acquisition patterns that a process model (or any other type of model) in the field of risky intertemporal choice should take into account. Our results also provide testable grounds for psychological assumptions in models of risky intertemporal choice: we found little evidence that participants treat probability and delay as representing a common factor of psychological distance, or that probability can be translated into delay, and vice-versa.

Acknowledgments

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