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Similarity in processes of risky choice and intertemporal choice: the case of certainty effect and immediacy effect

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Abstract: Risky choice (RC) and intertemporal choice (IC) are two types of common decisions that are vital to human's everyday life. RC and IC share similarities regarding theoretical development, behavioral effects, and neural basis. One critical challenge is that, although previous studies have revealed that RC and IC involve similar cognitive processes, results are mixed regarding what the exact mechanism might be. The mainstream discounting model hypothesizes that both RC and IC follow a compensatory and alternative-based rule. However, other models suggest that RC and IC commonly involve non-compensatory and attribute-based processing. Moreover, prior studies primarily based their findings on outcome data and few have attempted to determine whether RC and IC shared a common decision process at the cognitive computational level. To fill this gap, the present study adopts a systematic approach to disentangle the exact mechanism of RC and IC. We considered two well-studied behavioral effects, namely, certainty effect of RC and immediacy effect of IC, respectively, and compared their underlying local and holistic process characteristics by using eye-tracking technique. Besides, we employed hierarchical Bayesian modeling to assess whether alternative- or attribute-based models better fit both RC and IC. We designed a 2 × 2 within-subject paradigm, with the choice task (RC vs. IC) and the construct of decision options (with vs. without certain/immediate option) as factors. Thirty-three postgraduate students participated in our study. As we were particularly interested in two pairs of decision rules, namely, compensatory/non-compensatory rules and alternative-based/attribute-based rules, we included a series of decision attributes that reflected them, based on the local and holistic process characteristics derived from eye-movement data to test our hypotheses. Our entire set of analyses aimed to (1) determine whether the decision processes of RC and IC are similar and (2) identify the best computational model that is more suitable for both decisions. For the first aim, results show that RC and IC indeed share comparable decision processes, albeit having a few differences in other aspects. Specifically, RC and IC differ in process characteristics, such as complexity and holistic eye-movement dynamics, and IC is processed in a relatively more deliberate, deeper fashion than RC. However, they are similar in other characteristics, such as search direction, which is more relevant to making decisions. For the second aim, computational modeling of process characteristics suggests that both types of decisions are consistent with non-discounting models. In particular, results of search direction, in light of Bayesian model comparison, reveal that participants are more likely to follow the non-compensatory and attribute-based rule rather than the alternative-based/attribute-based rule when deciding for both RC and IC. Furthermore, different task constructs of decision options, namely, with or without certain/immediate option, show distinct process characteristics, such as direction, complexity, and depth in both RC and IC. To conclude, the present study shows that although differences exist between RC and IC, they indeed have shared cognitive mechanisms at the core of the decision processes. In both types of decisions, contrary to classic discounting models, individuals seem not to follow compensatory and attribute-based rules, which undergoes a weighting and summing or delay discounting process. Instead, they are more likely to use simple heuristic rules hypothesized by non-discounting models. Moreover, when including certain or immediate options, individuals tend to follow less compensatory and non-dominant (neither attribute-based nor alternative-based) rules. In sum, our findings not only provide a theoretical and empirical basis for the establishment of a common framework for RC and IC, but also provide a novel direction for thorough theoretical and methodological comparisons between variant decision tasks.

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1 Introduction

Risky choice and intertemporal choice are two important decisions closely related to human survival and development. RC refers to a decision made by people after weighing options with multiple outcomes and known probability of occurrence (Kahneman and Tversky, 1979), such as choosing different medical schemes. IC refers to the decision made by people after weighing alternatives that occur at different time points (Frederick, Loewenstein, and O'Donoghue, 2002), such as reducing over-exploitation and strengthening environmental protection. The two share similarities regarding theoretical development, behavioral effects and neural basis. Therefore, it is of great significance to explore whether they have a common mechanism for the development of universal decision theory and the simplification of decision concepts and models (Green, Myerson, and Vanderveldt, 2014). However, this problem remains controversial and lacks key evidence based on the decision-making process. Our understanding of this problem is hampered by the two limitations of current research, namely, the lack of key evidence based on the decision-making process and the inability of traditional hypothesis testing to accept null hypotheses. In recent years, the techniques of decision task process analysis and Bayes factor analysis have become more mature, and especially Bayes factor analysis can provide evidence for the establishment of null hypothesis and better compensate for the defects of significance hypothesis test of traditional null hypothesis (Wu, Gu, Shi, et al., 2018). Therefore, supplemented by the Bayes factor analysis, this paper is timely to use eye-tracking research to compare the processes of RC and IC, so as to explore and answer the scientific question whether the two have a common mechanism.

1.1 Similarity between RC and IC

1.1.1 Theoretical development

From the perspective of theoretical development, the two choices are very similar and both follow the path from the discounting model to the non-discounting model. Although these models have different hypotheses about specific computation rules, they both imply an important inference: the two have a common core algorithm.

The discounting model is derived from the unbounded rationality hypothesis. That is to say, individuals obtain all the information related to decision-making and obtain the optimal outcomes through logical and statistical reasoning or probability rule (Stevens, 2011). The commonality of such models is to assume that the decision follows the compensatory and alternative-based rules. That is to say, in order to make a decision, individuals need to process all the dimensions of the alternatives, integrate the internal information of each alternative and compare the utility size of the alternatives (Stevenson, Busemeyer, and Naylor, 1990): for example, RC has the classical expected value theory (Pascal, 1670) and a subsequent series of probability discounting theories, such as the prospect theory (Kahneman and Tversky, 1979); and similarly, IC has the classic discounted utility model (Samuelson, 1937) and the temporal discounting models developed based on it, such as the hyperbolic discounting model (Loewenstein and Prelec, 1992).

The non-discounting model is derived from the bounded rationality hypothesis proposed by Herbert Simon (winner of Nobel Prize in economics). That is to say, limited by the factors such as computing power and time, individuals have limited rationality in making decisions (Simon, 1982). The commonality of such models is to assume that the decision follows the non-compensatory and attribute-based decision rules. That is to say, individuals make decisions based on only a limited number of dimensions by comparing different dimensions (Stevenson et al., 1990): for example, RC has the priority heuristic model (Brandstätter, Gigerenzer, and Hertwig, 2006) and the equate-to-differentiate model (Li, 2004), and IC has the tradeoff model (Scholten and Read, 2010) and the drift diffusion model (Dai and Busemeyer, 2014).

1.1.2 Studies on analogy relationship between RC and IC

The theoretical similarity between RC and IC has led researchers to explore the essential relationship between the two, and most of these studies use the outcome-based or goodness-of-fit methods (Zhou, Zhang, Li, et al., 2018), which can be summarized into three categories. The first type of studies attempts to establish the compatibility model of the two. For example, based on the discounting model framework, Green, Myerson and Ostaszewski (1999) built a hyperbolic discounting model suitable for both and well fitted these two decisions. The second type of studies aims to find similar behavioral effects in these two decisions (Zhou, 2017). For example, RC has the certainty effect (Kahneman and Tversky, 1979), the pseudo-certainty effect (Kahneman and Tversky, 1984), the Allais paradox (Allais, 1953) and the hidden-zero effect (Liang, Zhou and Su, 2016), and correspondingly, IC has the immediacy effect (Kirby and Herrnstein, 1995), the pseudo-immediacy effect (Li, Su, and Sun, 2010), the falling flower paradox (Rao and Li, 2011) and the hidden-zero effect (Magen, Dweck, and Gross, 2008). The third type of studies examines the interaction of probability or time on these two decisions and explores whether they have the same impact on another type of choice (Hardisty and Pfeffer, 2016; Luckman, Donkin, and Newell, 2017). For example, Weber and Chapman (2005) found that adding the time variable to RC or adding the probability variable to IC would eliminate the certainty effect and the immediacy effect, which reveals that these two decisions might be equivalent.

In addition, these two decisions may have similar or even partially common neural bases. For example, studies have found that in RC, the activation of different brain regions can predict different behavioral patterns, such as nucleus accumbens activating the seeking of predictive risk, while anterior insula activating the avoidance of predictive risk (Kuhnen and Knutson, 2005). Similarly, in IC, people either assess the value of alternatives and make decisions through a single/separated nervous system (Kable and Glimcher, 2007; McClure, Laibson, Loewenstein, and Cohen, 2004), or produce preference inconsistencies through the role of self-controlling brain regions (Figner et al., 2010). A small number of studies have revealed that these two decisions are closely related to the brain regions associated with cognitive executive control (Weber and Huettel, 2008), as well as the brain regions associated with cognition and emotion (Wu, Zhou, and Luo, 2010).

1.1.3 Certainty effect and immediacy effect

Among the similar behavioral effects of these two decisions, the most classic ones are the certainty effect and the immediacy effect. The following preference reversals often occur in RC (Kahneman and Tversky, 1979): the certainty alternative A is preferred in Decision 1, but the risky alternative B’ is preferred in Decision 2 that has equal proportional changes of the two alternatives. This is the certainty effect.

Decision 1: A. obtaining USD 30 if probability is 100%; and B. obtaining USD 45 if probability is 80%;

Decision 2: A’. obtaining USD 30 if probability is 25%; and B’. obtaining USD 45 if probability is 20%.

Similarly, in IC, the immediacy alternative A is preferred in Decision 3, but the delay alternative B’ is preferred in Decision 4 that has equal proportional changes of the two options (Kirby and Herrnstein, 1995). This is the immediacy effect.

Decision 3: A. now obtaining USD 30; and B. obtaining USD 45 after one year;

Decision 4: A’. obtaining USD 30 after one year; and B’. obtaining USD 45 after two years.

These two effects are widely studied and very stable. In RC, certainty effect is found to occur in different tasks and situations set up by a variety of methods (Schneider, Streicher, Lermer, Sachs, and Frey, 2017). In IC, most researchers believe that immediacy effect is the root of the dynamic inconsistency of preference (Read, Loewenstein, and Kalyanaraman, 1999). It can be seen that the decision process of this pair of effects may be less disturbed by research methods.

Interestingly, there is a similar explanation mechanism for this pair of effects: individuals give too much weight to certainty and immediacy alternatives (Kahneman and Tversky, 1979; Kirby and Herrnstein, 1995). This implies that unlike other value points, when the probability and time delay information take values at the endpoints (probability is 100% or time is now), the certainty and immediacy information may have a strong correspondence, and influence people’s behavior preference through similar mechanism.

In summary, these two decisions may share a common effect mechanism. However, it is difficult for predecessors to test underlying cognitive processes using result-based methods (Schulte-Mecklenbeck et al., 2017). Therefore, it may be necessary to reveal the relationship between the two more accurately from the perspective of decision process.

1.2 Decision process: eye-movement study of RC and IC

Studies based on decision processes can overcome the limitations of results-based research methods and provide more direct and objective evidence for the correlation between information input and output of decision (Schulte-Mecklenbeck et al., 2017). Among them, the eye-tracking technique is widely used in decision process research due to the large amount of data and the ability to reflect both temporal and spatial characteristics (Wei and Li, 2015).

The eye-movement study of RC focuses on checking model and examining the relationship between eye-movement process and choice preference. For example, by analyzing characteristics such as processing direction, Li and his colleagues have found that the main processing of RC has non-compensatory and attribute-based characteristics and does not support the discounting model (Su et al., 2013; Wang and Li, 2012; Zhou et al., 2016). However, Glöckner et al. have found that RC is more in line with the parallel constraint satisfaction models based on the compensatory rules (Fiedler and Glöckner 2012; Glöckner and Herbold, 2011). Other studies revealed that features such as fixation transition and final fixation alternative can effectively predict the choice outcomes (Brandstätter and Körner, 2014; Stewart, Hermens, and Matthews, 2015).

There are relatively few eye-movement studies of IC, which mainly investigate the causal relationship between process characteristic and choice preference. For example, it is found that individuals with large time discount rates have attention bias to the immediacy alternative, and this preference can predict impulsive behavior (Franco-Watkins, Mattson, and Jackson, 2016). Therefore, manipulating attention preferences (Fisher and Rangel, 2013) or search strategies (Reeck, Wall, and Johnson, 2017) can prompt people to choose large and distant alternatives. However, there are rare studies of eye-movement examining the IC model.

1.3 Raise of problem

In summary, exploring the similarities between RC and IC helps to understand their common characteristics and develop their universality theory. However, the current research status hinders our understanding of this problem.

First, the classic discounting models of these two decisions assume that the two have similar processing process, but most of the existing research uses the result-based method. The result-based evidence is not convincing unless the internal mechanism of their similarity is revealed from the process perspective.

Second, the existing eye-movement studies have some shortcomings in the analysis methods and index selection. The classical models of these two decisions mostly imply the dynamic sequence process of information search and evaluation (Kahneman and Tversky, 1979). Therefore, it is necessary to examine their time series attributes from a holistic and dynamic perspective. However, few studies have selected indicators reflecting the holistic process characteristics, and even fewer have systematically adopted the multi-aspect characteristics based on local and holistic processes.

Third, previous studies show that there are some shortcomings in algorithm selection when establishing the compatibility model of the two. Based on the maximum likelihood estimation (MLE), most predecessors independently conducted model estimation on individuals (Green et al., 1999; Green et al., 2014), which lost the commonality of the overall level; moreover, as MLE did not consider the correlation between individuals, it caused model parameters to be noisy and unstable (Scheibehenne and Pachur, 2015), which was more obvious in the common small-sample decision research.

1.4 Research purposes and hypotheses

In order to overcome the above shortcomings, through the matching experimental paradigms and by taking certainty effect and immediacy effect as examples, this study adopted eye-tracking technique to compare the two types of decisions, and to explore whether the processing processes of the two were similar and which type of model hypothesis was more consistent with this processing.

This study has assumed that the two have similar behavior and process characteristics. In view of the fact that recent models are more based on non-discounting model framework (Scholten and Read, 2010; Dai and Busemeyer, 2014) and there is a large amount of process evidence supporting non-discounting model (Fisher and Rangel, 2013; Su et al., 2013), it is also assumed that both of them are more consistent with this model.

Based on behavioral, local and holistic process characteristics and model fitting, this study selects key process rules that can be used to distinguish models for comparison. Rule 1: compensatory/non-compensatory, that is, the decision is based on all or part of information and whether it contains a complex calculation process of careful processing. Rule 2: alternative-based/attribute-based, that is, the decision process takes place within or between alternatives (Stevenson et al., 1990). This study selected different eye-movement attributes as indicators for testing the local process characteristics in the above rules: processing complexity and processing depth test compensatory/non-compensatory rules, and processing direction test attribute-based/alternative-based rules; eye-movement trajectory is selected as an indicator to test the holistic process characteristics of decision; and the fitting method of hierarchical Bayesian modeling is used to fit the models with different alternative decisions.

The specific hypotheses are as follows.

Behavior characteristics:

H_1 (reaction time): there is no significant difference in decision time between the two.

H_2 (choice preference): RC has certainty effect, and IC has immediacy effect.

Local process characteristics:

H_3 (processing complexity): there is no significant difference in processing complexity between the two.

H_{4a} (processing depth): there is no significant difference in the percentage of fixation information between the two before making a decision.

H_{4b} (processing depth): neither needs to fixate all the alternatives before making a decision.

H_5 (processing direction): there is no significant difference in the frequency distribution between the alternative-based saccade and the attribute-based saccade.

Holistic process characteristics:

H_6: there is no significant difference in eye-movement trajectories between the two.

Model fitting:

H_7: compared with the discounting model, the two can be better fitted by the non-discounting model.

2 Methods

2.1 Subjects

This study selected 33 students (M_{age} = 26.72 years old, SD = 2.18 years old and N_{female} = 17 years old) from the University of Chinese Academy of Sciences and the Beijing Forestry University, who are right-handed, without daltonism and with normal vision or corrected vision. All of them signed the informed consent before the experiment.

Each subject can get CNY 30 basic reward and CNY 5–10 reward.

2.2 Instruments

This study adopted the Eye Link2000 eye tracker developed by SR Research, with the sampling rate of 2000 Hz and the shortest time of the fixation points is recorded as 40 ms. In the experiment, the chin rest which is 58 cm away from the display is adopted, and the automatic compensation mechanism of eye-tracking system is used to minimize the impact of head movement on eye-movement trajectory recording. The experimental stimuli were presented on a 19-inch TCL flat-screen display with a resolution of 1024 × 768. The horizontal and vertical visual angles of the subjects' eyes and the edge of screen were 28° and 21° respectively. The subjects responded by pressing keys on the Microsoft SideWinder gamepad.

2.3 Experimental materials and processes

This study used the within-subject design of 2 (tasks: RC/IC) × 2 (whether containing certainty/immediacy alternatives: containing/not containing). Subjects need to complete the tasks of RC and IC (in random order), and select the more preferred alternatives by pressing the keys. In the risky task, subjects choose between the two alternatives with different probabilities of occurrence: smaller-outcome, larger-probability (SL alternative for short) or larger-outcome, smaller-probability (LS alternative for short). Among them, under the condition of containing certainty alternative, each trial includes the certainty alternative A and the risky alternative B. The result (reward) of certainty alternatives CNY 300 or 700, and its expected value (EV) is slightly smaller than the EV of risky alternative (Kahneman and Tversky, 1979). The materials without certainty alternative condition are composed of the certainty alternative condition transformation: the probability of each alternative in the condition is obtained through the probability of obtaining the two options in certainty condition multiplying by the ratio less than 1, and the result of each alternative remains unchanged.

Similarly, in the intertemporal task, subjects choose between the two alternatives with different time: smaller-outcome, sooner (SS alternative for short) or larger-outcome, later (LL alternative for short). Among them, under the condition of containing immediacy alternative, each trial includes the immediacy alternative A and delay alternative B, and its alternative result (reward) is equal to that of RC. The materials without the immediacy alternative condition are composed of the material transformation of immediacy alternative condition: the acquisition time of this condition is the acquisition time of each alternative in the immediacy alternative condition plus a certain time, and the result of each alternative remains unchanged.

The task processes are shown in Figure 1. Before the task started, the subjects read the instructions and completed four exercises to get familiar with the task requirements. Each task contained 32 trials and was divided into 2 chunks. Subjects rested for at least one minute between chunks and at least two minutes between tasks. In order to ensure that each fixation of the subjects cannot acquire one additional piece of information (such as reward amount and payment time), all the information in the stimuli is presented in the edge area of other adjacent information, that is, the area outside the 5° visual angles from the center of other adjacent information (Rayner, 2013).

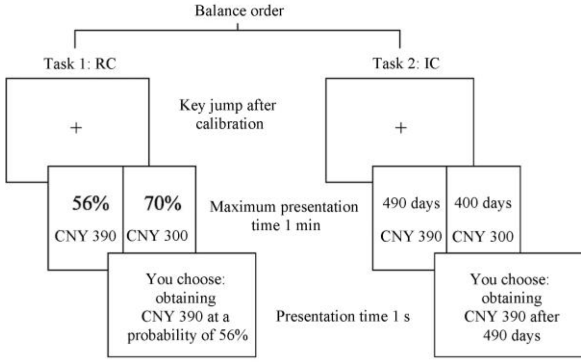

Fig. 1 Schematic diagram of the experimental processes

After the completion of all tasks, one trial was randomly selected in each task, and the actual choice of the subjects (according to a certain proportion) was taken as part of the experimental reward. Among them, in the risky task, if subjects selected the risky alternative, the computer would run a betting procedure with corresponding probability and outcome, and subjects would be rewarded with actual feedbacks. In the intertemporal task, subjects would be rewarded at the corresponding time based on the actual choices.

2.4 Data analysis method

The decision attributes, analysis indicators and methods tested by this study are shown in Figure 2.

2.4.1 Comparison of local process characteristics

Processing complexity: measured by the average duration of a single fixation point. The duration of fixation point is a reliable indicator reflecting the processing level. As the task difficulty increases, its duration also increases (Horstmann, 2009). If a compensatory rule is adopted for the decision, it may include a prudent calculation process and the average duration of the fixation point should be relatively long. Otherwise, it may not be based on the compensatory rule. In addition, this study also calculated the proportion of long fixation points in the decision process, which was as a supplement.

Processing depth: measured by the number of alternative characteristics that were fixated before making a decision (Su et al., 2013). If individuals process it according to the compensatory rule, all alternative characteristics should be processed before making a decision. Otherwise, they are more likely to process it according to the non-compensatory rule.

Processing direction: using SM values (alternative-based vs. dimension-based searched measure) (Böckenholt and Hynan, 1994) to measure the alternative-based and attribute-based saccade distributions. Its calculation formula is as follows:

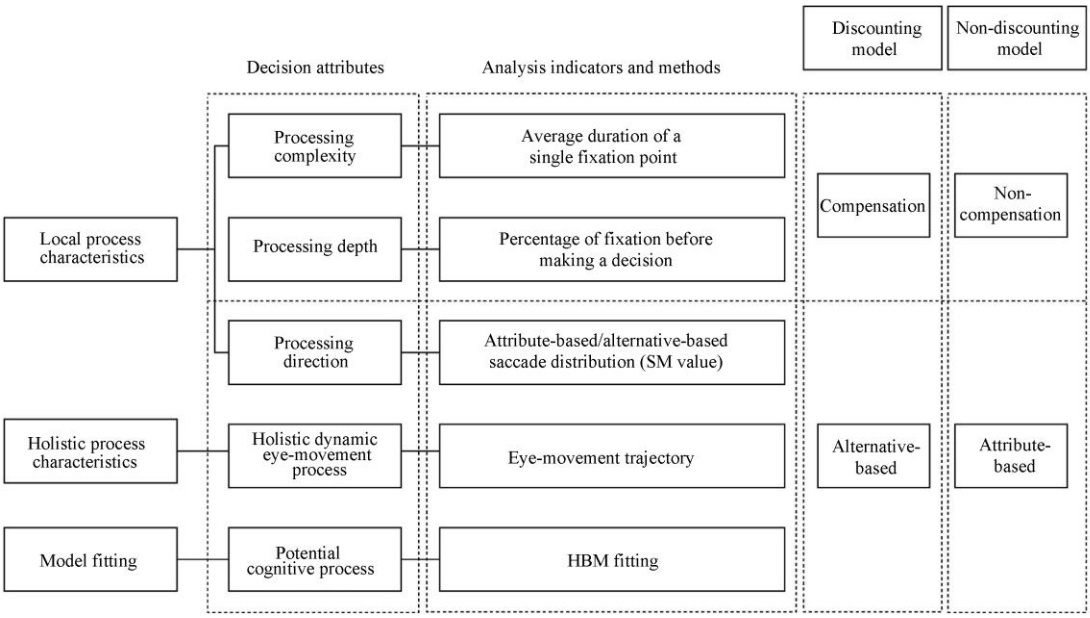

Fig. 2 Research logic and analysis framework

$$SM = \frac{\sqrt{N}\left(\frac{AD}{N}\right)(r_a - r_d) - (A - D)}{\sqrt{A^2(D-1) + D^2(A-1)}} \qquad (1)$$

In it, A and D respectively represent the number of alternatives and attributes (A = 2, D = 2); r_a and r_d respectively represent the frequencies of alternative-based and attribute-based saccade; N represents the total frequency of saccade; SM value is 0, which means that there is no dominant saccade pattern; compared with 0, the larger SM value represents that the main processing pattern of individuals is alternative-based, and on the contrary, it is more attribute-based.

SM value obeys the standard normal distribution and has been widely used in eye-movement research in decision-making (Konstantinidis, van Ravenzwaaij, and Newell, 2017; Schulte-Mecklenbeck, Kühberger, Gagl, et al., 2017; Su et al., 2013). The measurement indicator with SM value as the search pattern is suitable for testing the alternative-based and attribute-based decision models: when the number of alternatives and dimensions is manipulated, its mean value is stable and the probability of obtaining extreme values is extremely low (Böckenholt and Hynan, 1994). Compared with other indicators, it is more sensitive to the changes in search patterns: for example, by manipulating the search strategy to switch the dominant search pattern, SM value can detect this change sensitively (Böckenholt and Hynan, 1994). Therefore, in this study, if individuals process it according to the compensatory rule, the main processing direction of the decision is alternative-based, and SM value should be relatively large; on the contrary, it is more likely to be attribute-based.

2.4.2 Comparison of holistic process characteristics

This study selected the eye-movement trajectory to compare the holistic decision process. The eye-movement trajectory is driven by individuals' internalized cognitive model and is formed in a top-down cognitive processing mode, which reflects the brain's processing order of visual stimuli and the holistic dynamic eye-movement pattern (Noton and Stark, 1971). In order to intuitively observe the typical eye-movement trajectory pattern of different tasks, this study used the method of Zhou et al. (2016) to define a typical trial eye-movement trajectory. A typical trial refers to the trial with the largest (mean value) average similarity with other trials and the most representative under various experimental conditions. Therefore, the typical trial trajectory of a task is the most representative eye-movement trajectory pattern in the task, and is also the average eye-movement trajectory within the task condition when the similarity of eye-movement trajectory in the task is normally distributed.

The calculation steps of a typical trial are as follows. (1) Based on each condition, the similarity scores of all trials and other trials are calculated. (2) The average similarity scores of each trial and other trials are calculated. (3) The trial with the largest average similarity score with other trials under each condition is selected and defined as the typical trial of the conditions. Therefore, in this study, (1) if there is no significant difference between the similarity scores of intra-condition and inter-condition for the eye-movement trajectory of RC and IC tasks, it indicates that the holistic processing of the two are similar; otherwise, they are not similar. (2) If the typical trial of a task has the processing process assumed by the accounting model, it can be qualitatively judged that the decision may be based on the compensatory and alternative-based rules, and on the contrary, it does not meet the hypotheses of discounting model.

2.4.3 Comparison of model fitting

In order to answer which theoretical model is more suitable for the processes of RC and IC, this study used the HBM method to fit the decision models with different alternatives. Compared with MLE, the advantages of HBM method lie in the following (Gelman et al., 2014; Ahn, Haines, and Zhang, 2017). HBM adopts the hierarchical model, adjusts the individual-level parameters by introducing the group-level parameters. At the same time, it simultaneously estimates these parameters based on the observed data, which makes the model fitting more efficient, stable and reliable. MLE mostly performs point estimation, and HBM uses Markov chain Monte Carlo (MCMC) algorithm to sample and approximate the most likely distribution shape of parameters, so as to obtain the posterior distribution of model parameters, which can provide more information. These two advantages are particularly effective for laboratory studies with small samples. Finally, based on the Bayesian principle, this method can calculate the difference of posterior distribution of parameters for the comparison among groups (Scheibehenne and Pachur, 2015; Ahn et al., 2017).

HBM fitting uses the R software package hierarchical Bayesian modeling of Decision-Making tasks (Ahn et al., 2017). Four independent MCMC chains are used for all model fitting, and each chain contains 1000 valid samples, so the posterior distribution of all parameters is composed of 4000 valid samples. The Gelman-Rubin test (Gelman and Rubin, 1992) showed that the

$\hat{R}$ of all parameters is less than 1.1, indicating that the four independent MCMCs are gathered and the results of model fitting are stable and reliable. Widely applicable information criterion (WAIC) (Vehtari, Gelman, and Gabry, 2015) is used as the basis for Bayesian model comparison. WAIC uses all MCMC posterior samples to calculate the out-of-sample predictive accuracy of the model. In order to avoid overfitting, the number of parameters is penalized in the model comparison, and the model complexity is taken into account. The smaller the WAIC value is, the stronger the out-of-sample predictive accuracy of the model is. If ΔWAIC > 10, it can be considered as significant difference (Burnham and Anderson, 2004).

The calculation formula of WAIC is as follows:

$$WAIC = -2(\text{lpd} - \hat{p}_{waic}) \tag{2}$$

In it, *Ipd* indicates the computed log pointwise predictive density. Its corresponding goodness-of-fit is as follows:

$$\text{lpd} = \sum_{i=1}^{n} \log\left(\frac{1}{S}\sum_{S=1}^{S} p(y_i \mid \theta^S)\right) \tag{3}$$

$\hat{p}_{\text{waic}}$ indicates the estimated effective number of parameters. Its corresponding model complexity is as follows:

$$\hat{p}_{\text{waic}} = \sum_{i=1}^{n} Var_{S=1}^{S}(\log(p(y_i \mid \theta^S))) \tag{4}$$

This study selected three theoretical models to carry out model fitting and parameter estimation for the tasks of RC and IC. Among them, the classic discounting model chose the exponential model (Model 1) (Samuelson, 1937) and the hyperbolic model (Model 2) (Mazur, 1987). The core hypothesis of the two is as follows: according to the alternative-based rules, individuals make decisions, calculate the discount rates and select the alternatives with high subjective utility.

The non-discounting model chose the intertemporal choice heuristic (ITCH, Model 3) (Ericson, White, Laibson, et al., 2015). Its core hypothesis is as follows: according to a heuristic strategy composed of a series of rules based on attribute-based comparison, individuals make decisions, assign different rules with different weights and select better alternatives according to these rules. As the proposed model is based on psychological rules rather than economic theories, it can be used to test attribute-based processing rules. Moreover, under different task conditions, the model parameters are relatively stable and are less affected by parameter situation and experimental manipulation. In addition, compared with the DRIFT heuristic model (Read, Frederick, and Scholten, 2013) and the trade-off model (Scholten and Read, 2010), it has a slightly higher explanatory power for individuals' behavior results (Ericson et al., 2015).

The formulas of each theoretical model are as follows:

$$V = A * e^{-kD} \tag{5}$$

$$V = A / (1 + kD) \tag{6}$$

$$p(LL) = L\left(\begin{pmatrix}\beta_I \\ \beta_{xA} \\ \beta_{xR} \\ \beta_{dR} \\ \beta_{dR}\end{pmatrix} * \begin{pmatrix}1 \\ X_{LL} - X_{SS} \\ (X_{LL} - X_{SS}) / X^* \\ D_{LL} - D_{SS} \\ (D_{LL} - D_{SS}) / D^*\end{pmatrix}\right) \tag{7}$$

$$X^* = \frac{(X_{LL} + X_{SS})}{2} \quad D^* = \frac{(D_{LL} + D_{SS})}{2}$$

Taking IC as an example, in Model 1 (Equation 5) and Model 2 (Equation 6), *V* represents the subjective utility of individuals to alternatives, *A* represents the result of future alternatives, *e* represents the base of natural logarithms, *D* represents the delay time, *k* represents the discount rate; and in Model 3 (Equation 7), X_{LL} represents the result of LL alternatives, X_{SS} represents the result of SS alternatives, D_{LL} represents the time of LL alternatives, D_{SS} represents the time of SS alternatives, and β is a series of free parameters that represent the weight of all items in the regression equation.

By analyzing the advantages and disadvantages of each model fitting indicator in each decision task, it can judge whether the two types of tasks can be better fitted by the same model. If the goodness-of-fit of discounting model on the task is better than that of non-discounting model, it means that these two decisions are more consistent with the hypotheses of discounting model; otherwise, they are consistent with those of non-discounting model.

3 Results

Eye-movement data is exported and pre-processed by Eyelink Data Viewer (SR Research, Canada). Saccade is defined as a single eye-movement with a speed exceeding 30 °/s and an acceleration exceeding 8000 °/s^2; and the fixation is defined as a period of time in which the eye position is relatively stable between two saccades. Each stimulus material is divided into four non-overlapping rectangular interest regions with the same area (200 × 180 pixels), covering all the attributes of two alternatives.

There were 2112 formal trials in this study, and 36 trials (1.56%) were excluded in the data analysis, of which 19 (0.90%) were eye-tracking errors, and 17 were the ones with too short reaction time (< 200 ms) or too long reaction time (3 standard deviations above the average reaction time). Therefore, there remained 2076 valid trials. In addition, a total of 18,720 fixation points were collected in the eye-movement trajectory analysis. Because the duration of some fixation points was less than 50 ms or the locations of some points were outside the interest regions, 936 (about 5.00%) fixation points were excluded from the subsequent analysis. Therefore, there remained 17,784 valid fixation points.

In view of the uniqueness of the research problem, in addition to the traditional hypothesis test, this paper adopted the Bayes factor analysis in the data analysis to test whether the processes of these two decisions are the same, that is, whether to accept the null hypothesis. The advantage of Bayes factor analysis is that H_0 and H_1 can be considered simultaneously, and based on the experimental data, the prior probabilities with the two true hypotheses can be updated to compare which theoretical model (H_0 and H_1) is more reasonable (Hu, Kong, Wagenmakers, et al., 2018). This compensates for the limitations of traditional hypothesis testing. That is to say, it cannot accept the null hypothesis, and ignore the situation that H_0 may be bigger than H_1. Therefore, by calculating the size of Bayes factor, it can judge to what extent the null hypothesis can be accepted. This study used JASP software to analyze the Bayes factor (https://jasp-stats.org/, JASP team 2017) (JASP Team, 2017; Marsman and Wagenmakers, 2017; Wagenmakers et al., 2018a; Wagenmakers et al., 2018b). Among them, the prior distribution uses the $\gamma \approx 0.707$ Cauchy distribution [①] (Jeffreys, 1961; Ly, Verhagen, and Wagenmakers, 2016a, 2016b; Rouder, Speckman, Sun, et al., 2009; Hu et al., 2018).

3.1 Behavioral characteristics

3.1.1 Decision time

After performing the 2 (tasks: RC/IC) × 2 (whether containing certainty/immediacy alternatives: containing/not containing) repeated measures analysis of variance (ANOVA) on the reaction time, the following has been found (Fig. 3): the decision time of risky task (M = 2.81 s, SD = 0.92) is shorter than that of intertemporal task (M = 3.24s, SD = 1.09), $F(1, 32) = 4.62$, $p = 0.04$, $\eta^2 = .13$, 95% CI[−0.83, −0.02]; the decision time without the certainty/immediacy alternative conditions (M = 3.65 s, SD = 0.92 s) is longer than that with the certainty/immediacy alternative conditions (M = 2.40 s, SD = 0.80 s), $F(1,32) = 108.69$, $p < 0.001$, $\eta^2 = 0.77$, 95% CI[1.01, 1.50]. Simple effect test (interaction: $F(1, 32) = 9.86$, $p = 0.004$, $\eta^2 = 0.24$) shows that, under the absence of the certainty/immediacy alternatives, the reaction time of risky task (M = 3.26 s, SD = 5.28s) was significantly shorter than that of the intertemporal task (M = 4.04 s, SD = 7.76 s), $F(1, 32) = 11.51$, $p = 0.002$; but under the certainty/immediacy alternatives, the reaction time of risky task (M = 2.36 s, SD = 5.63 s) is not significantly different from that of intertemporal task (M = 2.43s, SD = 6.26s), $F(1, 32) = 0.09$, $p = 0.77$. The results of Bayes factor analysis shows that Bayes factor $BF_{01} = 5.15$, indicating that it is 5.15 times more likely that the current data will appear under the null hypothesis (assuming no effect) than under the alternative hypothesis (assuming effect). According to the classification criteria proposed by Jeffreys (1961), this is moderate evidence supporting the acceptance of the null hypothesis H_0. That is to say, there is no significant difference in these two decision time under the certainty/immediacy alternative conditions. In summary, the results of the decision time partially support H_1.

3.1.2 Choice preference

The study conducted a paired-sample t-test by taking the proportion of SL alternative and SS alternative as the dependent variable. In the risky task, the proportion of people choosing SL alternative (M = 0.83, SD = 0.28) under the condition of containing certainty alternative is higher than that not containing it (M = 0.56, SD = 0.17), $t(32) = -5.17$, $p < 0.01$, Cohen's $d = -0.90$, 95% CI[−0.38, −0.17]. Similarly, in the intertemporal task, the proportion of people choosing SS alternative (M = 0.68, SD = 0.34) under the condition of containing immediacy alternative is higher than that not containing it (M = 0.34, SD = 0.23), $t(32) = -6.74$, $p < 0.001$, Cohen's $d = -1.17$, 95% CI[−0.45, −0.24]. This result shows that at the behavioral level, both certainty effect and immediacy effect are repeated, which supports H_2.

[①] The Cauchy distribution with lower relative probability density of 1 near 0 allows larger effects, so it is considered to be more suitable for the prior distribution of the alternative hypothesis (Jeffreys, 1961; Ly, Verhagen, and Wagenmakers, 2016a, 2016b; Rouder et al., 2009).

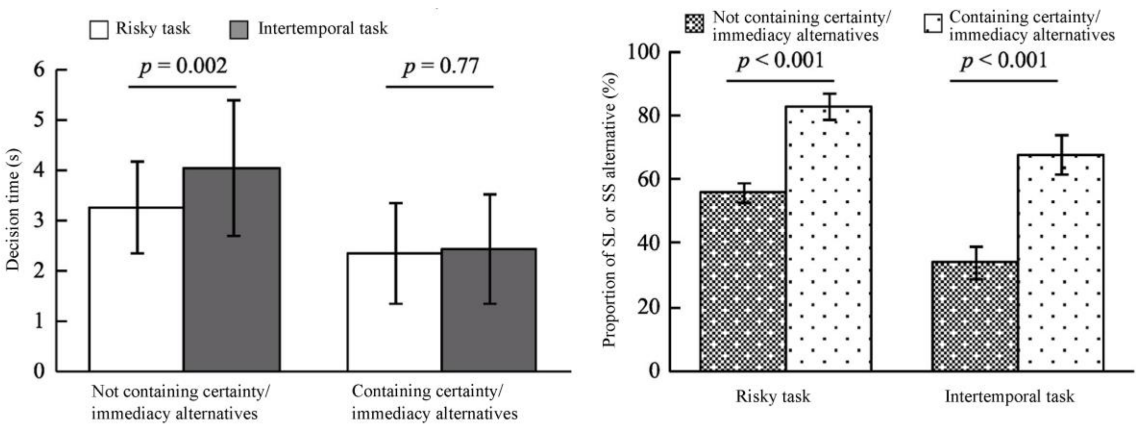

Fig. 3 Comparison results of behavior characteristics

3.2 Local process characteristics

3.2.1 Processing complexity

With the average duration of a single fixation point as the dependent variable, the repeated measurement ANOVA of the two factors (tasks × whether containing certainty/immediacy alternatives) has found (Fig. 4) that there is no difference in the average duration of a single fixation point between the two tasks, $F(1, 32)= 0.63$, $p = 0.43$, 95% CI[−13.23, 5.82]; the average duration of a single fixation point (M = 224.64 ms, SD = 33.61 ms) not containing certainty/immediacy alternatives is higher than that containing them (M = 208.33 ms, SD = 34.01 ms), $F(1, 32) = 19.76$, $p < 0.001$, $\eta^2 = 0.38$, 95% CI [8.84, 23.79]. The results of simple effect test (interaction: $F(1, 32) = 5.63$, $p = 0.02$, $\eta^2 = 0.15$) show that the average duration of a single fixation point of risky task (M = 218.73 ms, SD = 40.21 ms) is significantly shorter than that of intertemporal task (M = 230.55 ms, SD = 32.97 ms) when certainty/immediacy alternatives are excluded, $F(1, 32) = 5.19$, $p = 0.03$, η^2=0.14; there is no significant difference in the average duration of a single fixation point (M = 210.53 ms, SD = 45.73 ms) between risky task and intertemporal task (M = 206.13 ms, SD = 29.81 ms) when certainty/immediacy alternatives are included, $F(1, 32) = 0.48$, $p = 0.49$. Bayes factor analysis shows that Bayes factor $BF_{01} = 4.29$, indicating that the probability of presenting the current data under the null hypothesis is 4.29 times higher than that under the alternative hypothesis, and there is moderate evidence supporting the acceptance of the null hypothesis H_0 (Jeffreys, 1961). That is to say, there is no significant difference in the average duration of a single fixation points between risky task and intertemporal task when certainty/immediacy alternatives are included. In summary, the results partially support H_3. As a supplement, fixation points with a duration longer than 300 ms are taken as long fixation points (Rayner, 2013), and their proportions are analyzed. The results are similar to the average duration of a single fixation point, and it is revealed that both the processing processes of these two tasks are more in line with non-compensatory rules.

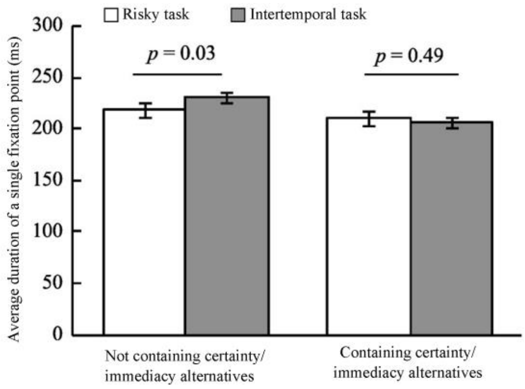

Fig. 4 Comparison results of process characteristics of processing complexity

3.2.2 Processing depth

With the percentage of alternative characteristics of pre-decision fixation to all alternative characteristics (hereinafter referred to as percentage of fixation) as the dependent variable, the repeated measurement ANOVA of the two factors (tasks × whether containing certainty/immediacy alternatives) has found (Fig. 5) that there is no significant difference between the percentage of fixation of risky task (M = 93.10%, SD = 8.04%) and the percentage of fixation of intertemporal task (M = 94.20%, SD = 7.47%), $F(1, 32) = 0.57$, $p = 0.46$, 95% CI[−0.04, 0.20]; and the percentage of fixation (M = 97.50%, SD = 0.70%) not containing certainty/immediacy alternatives are significantly higher than that containing it (M = 89.70%, SD =9.77%), $F(1, 32) = 30.10$, $p < 0.001$, $\eta^2 = 0.49$, 95 %CI[0.05, 0.11]. The results of simple effect test (interaction: $F(1, 32) = 0.563$, $p = 0.46$) show that the difference between the percentage of fixation in risky task (M = 96.48%, SD = 6.32%) and that in intertemporal task (M = 98.58% ,SD = 2.88%) is marginal significant when certainty/immediacy alternatives are excluded, $F(1, 32) = 3.99$, $p = 0.054$; but there is no significant difference between the percentage of fixation in risky task (M = 89.63%, SD = 11.36%) and that in intertemporal task (M = 89.87%, SD = 13.40%) when certainty/immediacy alternatives are included, $F(1, 32) = 0.008$, $p = 0.93$. Bayes factor analysis has found that Bayes factor $BF_{01} = 5.35$, indicating that the probability of presenting the current data under the null hypothesis is 5.35 times higher than that under the alternative hypothesis, and there is moderate evidence supporting the acceptance of the null hypothesis H_0 (Jeffreys, 1961). That is to say, there is no significant difference in the percentages of fixation between risky task and intertemporal task when certainty/immediacy alternatives are included. In summary, the results support the hypothesis H_{4a}.

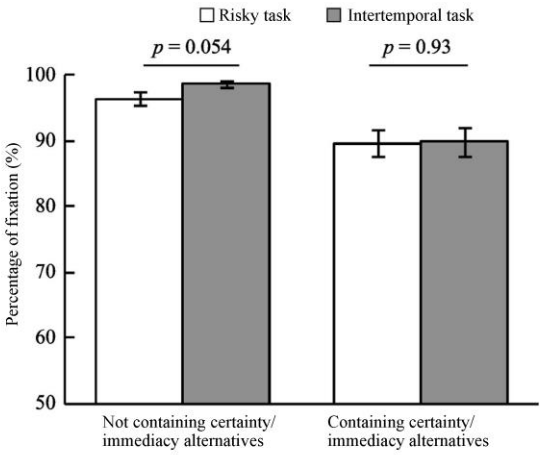

Fig. 5 Comparison results of process characteristics of processing depth

After the study respectively performed a single-sample t-test (single tail) on the percentages of fixation of risky task and intertemporal task and the 100% of fixation of these tasks, it was found that the percentages of fixation were both significantly lower than 100% in risky task and intertemporal task ($t_1(32) = -5.00$, $p_1 < 0.001$, Cohen's $d_1 = -0.87$; $t_2(32) = -4.45$, $p_2 < 0.001$, Cohen's $d_2 = -0.77$). It showed that both task processes are more consistent with the hypothesis of non-compensatory processing and support H_{4b}.

3.2.3 Processing direction

The repeated measurement ANOVA for SM value shows (Fig. 6) that there is no significant difference between the mean SM value of risky task ($M = 0.09$, $SD = 0.63$) and the mean SM value of intertemporal task ($M = 0.27$, $SD = 0.69$), $F(1, 32) = 1.36$, $p = 0.25$, 95% CI[−0.14, 0.52]; and the SM values not containing certainty/immediacy alternatives ($M = -0.42$, $SD = 0.52$) are significantly lower than those containing them ($M = 0.06$, $SD = 0.52$), $F(1, 32) = 67.61$, $p < 0.001$, $\eta^2 = 0.68$, 95% CI[−0.59, −0.36]). The results of simple effect test (interaction: ($F(1, 32) = 8.79$, $p = 0.01$, $\eta^2 = 0.22$) show that the difference between the mean SM value of risky task ($M = -0.23$, $SD = 0.69$) and that of intertemporal task ($M = -0.60$, $SD = 0.84$) is marginal significant when certainty/immediacy alternatives are excluded, $F(1, 32) = 3.41$, $p = 0.07$. Bayes factor analysis has found that Bayes factor $BF_{01} = 1.18$, indicating that the probability of presenting the current data under the null hypothesis is 1.18 times higher than that under the alternative hypothesis, and there is weak evidence supporting the acceptance of the null hypothesis H_0 (Jeffreys, 1961) There is no significant difference between the mean SM value of risky task ($M = 0.06$, $SD = 0.64$) and that of intertemporal task ($M = 0.05$, $SD = 0.57$) when certainty/immediacy alternatives are included, $F(1, 32) = 0.001$, $p = 0.98$. Bayes factor analysis has found that Bayes factor $BF_{01} = 5.37$, indicating that the probability of presenting the current data under the null hypothesis is 5.37 times higher than that under the alternative hypothesis, and there is moderate evidence supporting the acceptance of the null hypothesis H_0 (Jeffreys, 1961). That is to say, there is no significant difference in the SM values of risk task and intertemporal task when certainty/immediacy alternatives are included. The above results indicate that risky task and intertemporal task are similar in processing direction, which partially support H_5.

Further, after a single-sample t-test (single tail) is respectively performed on the SM value of risky task and intertemporal task and 0 under the two conditions, it has been found that there is no significant difference between SM value of risky task and 0 when certainty alternative is included, $t(32) = 0.92$, $p = 0.30$. Bayes factor analysis has found that Bayes factor $BF_{01} = 4.74$, indicating that the probability of presenting the current data under the null hypothesis is 4.74 times higher than that under the alternative hypothesis, and there is moderate evidence supporting the acceptance of the null hypothesis H_0 (Jeffreys, 1961). That is to say, there is no dominant saccade pattern in risky task; and there is no significant difference between SM value of intertemporal task and 0 when immediacy alternative is included, $t(32) = 0.92$, $p = 0.29$. Bayes factor analysis has found that Bayes factor $BF_{01} = 4.67$, indicating that the probability of presenting the current data under the null hypothesis is 4.67 times higher than that under the alternative hypothesis, and there is moderate evidence supporting the acceptance of the null hypothesis (Jeffreys, 1961). That is to say, there is no dominant saccade pattern in intertemporal task. The SM values of both risky task and intertemporal task are significantly less than 0 when certainty/immediacy alternatives are excluded, ($t_1(32) = -1.90$, $p = 0.03$, Cohen's $d = -0.33$; $t_2(32) = -4.12$, $p < 0.001$, Cohen's $d = -0.71$). The above results indicate that risky task and intertemporal task have no dominant saccades when certainty/immediacy alternatives are included, and they are more attribute-based when certainty/immediacy alternatives are excluded.

3.3 Holistic process characteristics

Single-factor repeated measurement ANOVA was respectively performed with the similarity score of eye-movement trajectory as the dependent variable under the conditions of containing/not containing certainty/immediacy alternatives. Results show (Fig. 7) that there are significant differences in similarity scores of eye-movement trajectories

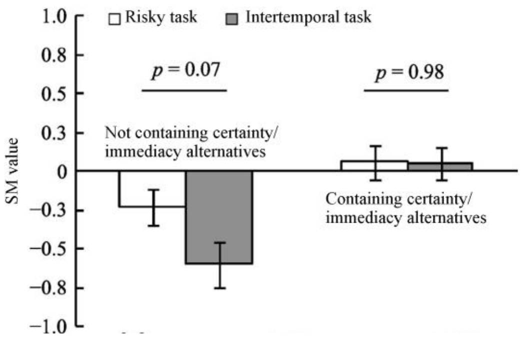

Fig. 6 Comparison results of process characteristics of processing direction

within and out of RC task and IC task when certainty/immediacy alternatives are excluded, $F(1, 32) = 16.82$, $p < 0.001$, $\eta^2 = 0.35$, 95% CI [0.45, 0.49]. Posterior comparisons (Tukey Honestly Significant Difference (HSD) method) show that the similarity scores of eye-movement trajectories between the two tasks ($M_1 = 0.44$, $SD_1 = 0.06$) are all significantly lower than those within RC task ($M_1 = 0.50$, $SD_1 = 0.05$, $p_1 < 0.001$) and within IC task ($M_2 = 0.47$, $SD_2 = 0.07$, $p_2 = 0.007$). There are significant differences in the similarity of eye-movement trajectories within and out of the two tasks when certainty/immediacy alternatives are included, $F(1, 32) = 10.58$, $p < 0.001$, $\eta^2 = 0.24$, 95% CI[0.47, 0.49]. Posterior comparisons (Tukey HSD) show that the similarities of eye-movement trajectories between the two tasks ($M_1 = 0.46$, $SD_1 = 0.05$) are significantly lower than those within the RC task ($M_1 = 0.50$, $SD_1 = 0.03$, $p_1 = 0.001$) and within the IC task ($M_2 = 0.48$, $SD_2 = 0.06$, $p_2 = 0.01$). This result rejects H_6, indicating that the eye-movement trajectories of RC and IC, namely, the holistic dynamic process characteristics of the two, are not similar.

The typical trials of risky task and intertemporal task are shown in Figure 8. The results of K-S test show that the similarity scores of within risky task (not containing certainty: $z = 0.14$, $p = 0.13$; containing certainty: $z = 0.09$, $p = 0.20$) and intertemporal task (not containing immediacy: $z = 0.06$, $p = 0.20$; containing immediacy: $z = 0.09$, $p = 0.20$) all conform to normal distribution. Therefore, the trajectories of typical trials can represent the average eye-movement trajectories within the task conditions. By observing the typical trials, it can be found that, relatively speaking, there are more attribute-based saccades in risky task, but the IC task does not show a similar eye-movement pattern in the holistic eye-movement pattern. In addition, similar to the SM value results, there are more attribute-based saccades when certainty/immediacy alternatives are excluded, and there are more alternative-based saccades when certainty/immediacy alternatives are included.

3.4 HBM fitting

In this study, the exponential model, the hyperbolic model and the heuristic model were respectively used to fit risky task and intertemporal task. The results have found that (Table 1), regardless of risky task or intertemporal task, compared with the classical discounting models based on alternative processing (Model 1 and Model 2), the heuristic model based on dimension processing (Model 3) has higher fitting degree for risky task and intertemporal task, and WAIC is significantly lower than the other two models. Moreover, the prediction rate of heuristic model on the results of the two tasks is as high as 80%, which can more accurately predict the individuals' choice than the discounting model. The above results support H_7. According to the theoretical hypothesis of ITCH model, it can be inferred that individuals may adopt a series of strategies combined by simple heuristic rules in both RC and IC. For example, comparison between outcome dimension and probability/time dimension is carried out before making a decision.

Table 1 HBM fitting results

Model categories	Model	RC task		IC task	
		WAIC	Prediction rate	WAIC	Prediction rate
Discounting model	Exponential model	1169.51	61.79%	885.61	71.60%
	Hyperbolic model	1325.38	54.91%	787.39	76.01%
Non-discounting model	Heuristic model	682.42	80.46%	595.59	84.32%

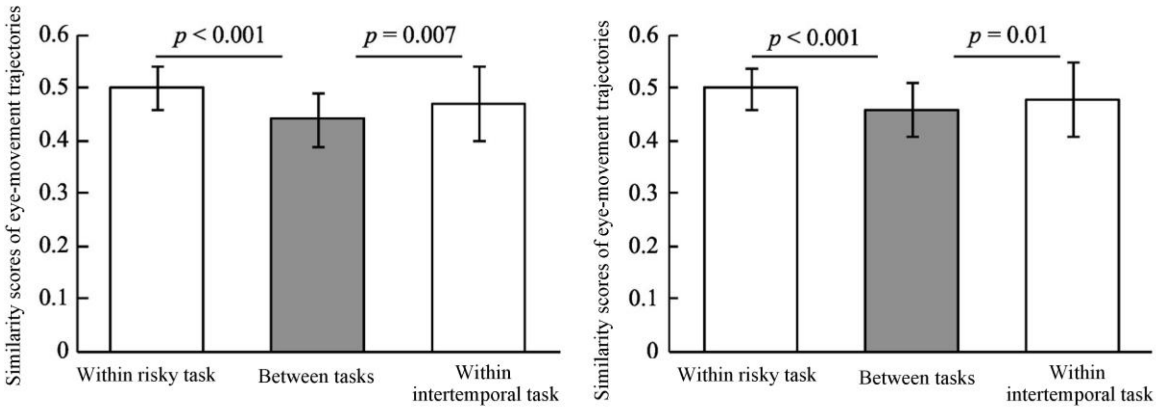

Fig. 7 Comparison results of similarity scores of eye-movement trajectories (M ± SE)

(Left: not containing certainty/immediacy conditions, right: containing certainty/immediacy conditions)

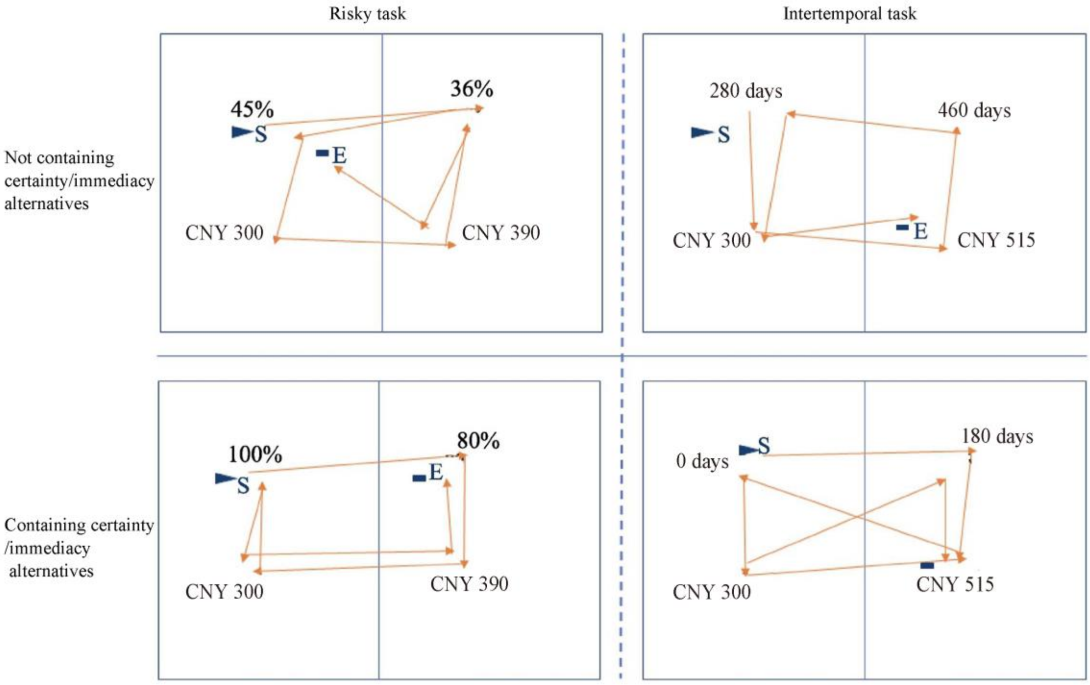

Fig. 8 Eye-movement trajectories of typical trials in each task condition

Note: the arrow represents the direction of eye-movement trajectories, *S* represents the starting position, and *E* represents the ending position.

Table 2 Summary of process characteristic test and model fitting results

Decision characteristic	Decision attributes	Analysis indicators	Decision process rules			
			Risky task		Intertemporal task	
			Containing certainty/ immediacy alternatives	Not containing certainty/ immediacy alternatives	Containing certainty/ immediacy alternatives	Not containing certainty/ immediacy alternatives
Local process characteristic	Processing complexity	Average duration of a single fixation point/proportion of long fixation points	Non-compensation	Non-compensation	Non-compensation	Non-compensation
	Processing depth	Percentage of fixation	Non-compensation	Non-compensation	Non-compensation	Non-compensation
	Processing direction	SM value	No dominant rules	Attribute-based	No dominant rules	Attribute-based
Holistic process characteristic	Holistic dynamic eye-movement process	Eye-movement trajectory	No dominant rules	Attribute-based	No dominant rules	No dominant rules
Model fitting	Potential cognitive process	HBM fitting	Attribute-based	Attribute-based	Attribute-based	Attribute-based

4 Discussions

Taking certainty effect and immediacy effect as examples, this study comprehensively compared RC and IC from behavior characteristics and local and holistic process characteristics, and tested whether these two decisions are more consistent with the prediction of non-discounting model through HBM fitting. The results show that for behavior characteristics, individuals' excessive preference for certainty/immediacy alternatives shows certainty effect and immediacy effect. For local process characteristics, the processing depth attributes of the two are similar under all parameters; however, the processing direction, the attributes of processing direction and complexity are similar only under the condition of parameters including certainty/immediacy alternatives. For the holistic process characteristics, the two have different holistic dynamic eye-movement processes. For model fitting, both of them have similar underlying cognitive processes and can be better fitted by non-discounting models. The above results show that RC and IC share a common process mechanism in most of the tested attributes. What is more, they do not meet the hypothesis of discount calculation of the compensatory model in the processing process, and are more in line with the hypothesis of non-compensatory ITCH model, which may adopt a series of strategies combined by heuristic rules to make a decision.

4.1 Common process mechanism for RC and IC

Based on the decision characteristics of compensatory/non-compensatory and attribute-based/

alternative-based rules, this study explored the common process mechanism of these two decisions. It is found that the core processing rules of the two are non-compensatory and attribute-based.

Among them, the results of processing depth and complexity indicate that both meet the non-compensatory processing rules: people do not process all alternative characteristics before making decisions, but make decisions based on partial information; and the processing process may not include prudent and complex computational process. This result is consistent with the findings of previous researchers such as Stewart et al. (2015) and Glöckner and colleagues (2011, 2012). This study has found that the average duration of a single fixation point in these two decision processes is relatively short (average 216 ms), which does not meet the expectation of compensatory rules and more supports the hypothesis of heuristic decision rules. In addition, the number of alternative characteristics of pre-decision fixation in this study is 93.6%, which is higher than the average fixation of 88.50% reported by Su et al. (2013). This may be due to the fact that this study used the single-result decision task, while Su et al. (2013) used the dual-result decision task. It can be inferred that as the task complexity increases, people will pay less attention to the information before making decisions and will not conduct compensatory processing.

The results of processing direction and model fitting show that both of them conform to the attribute-based processing rules: people search and process information more according to dimensions in decision-making, which conforms to the prediction of heuristic model. This result is consistent with the findings of Su et al. (2013) and Fisher et al. (2013), indicating that in the process of information comparison of these two decisions, the dominant search pattern is attribute-based comparison. Moreover, the processing process of this attribute-based comparison can be truly detected by the eye-movement process, and can be verified by model fitting. What is more, the two results are consistent and more in line with the ITCH model hypothesis. That is to say, decision makers may use a combination of a series of different heuristic rules in their RC and IC (such as the comparison of absolute and relative differences in different dimensions), and people assign different weights to the use of different rules (Ericson et al., 2015). This paper only selected ITCH as the representative of attribute-based processing model, and the explanatory power of attribute-based processing model family is not significantly different when considering the research of different processing models (Ericson et al., 2015), but both of them perform better than the alternative-based processing models (Dai and Busemeyer, 2014; Scholten and Read, 2010). Therefore, it can be inferred that if other heuristic models are used in future research, similar results may be obtained: compared with the discounting model based on alternative processing, the heuristic model based on dimension processing has a higher fitting degree for risky task and intertemporal task.

It should be noted that Bayes factor analysis showed that, in the absence of certainty/immediacy alternatives, only weaker evidence supports the consistency of the processing directions of these two decisions. However, considering the significant difference between SM value and 0 value (namely, the shown attribute-based processing), these two decisions are similar in processing direction qualitatively.

In summary, this study has confirmed that the discount calculation (or weighted summation) process accepted in the mainstream decision theory is not necessarily applicable to RC and IC. Therefore, future research should consider the non-discounting model when attempting to establish a common theoretical framework between the two.

4.2 Specificity of RC and IC processes

The study also found that these two decisions have specificities in a few behavior and process characteristics: compared with RC, people take longer time to make IC, have higher processing complexity and processing depth (not containing certainty/immediacy alternatives), and obtain more significant attribute-based comparison characteristics in terms of holistic process characteristics. Especially in observing the results of typical trials, it can be seen that the difference between the two in the holistic dynamic eye-movement process may be reflected in the pattern of information comparison: in the risky task not containing certainty alternative, individuals successively compare the information based on probability and outcome dimensions and then make decisions. However, similar eye-movement pattern is not reflected in IC.

There are two possible reasons for these specificities. First, compared with the IC, RC may be closer to automated and parallel processing mode, while people may have higher degree of prudence or processing difficulty when making IC, especially when immediacy alternative is excluded. Second, some materials of these two tasks in the study (not containing certainty/immediacy alternatives) only match the size of the results, but do not match the probability and time equally according to their psychological feelings. For example, if one obtains CNY 300 at the 45% probability, it may not be equivalent to obtaining CNY 300 after 280 days. In order to avoid the confusion caused by parameter differences, the matching experiment parameters can be set for these two decision tasks in future research.

4.3 Specificity of certainty information and immediacy information in RC and IC processes

This study has found that whether these two decisions contain certainty/immediacy alternatives are different in each local process characteristic, indicating that individuals have specificities on the processing of certainty information and immediacy information: when certainty/immediacy alternatives are excluded, people tend to make decisions based on compensatory rules and attribute-based rules; when certainty/immediacy alternatives are excluded, the processing complexity of decision is higher, the processing depth is deeper, and the processing direction is more attribute-based; but when certainty/immediacy alternatives are included, there is no dominant pattern in processing direction.

The specificity of certainty/immediacy alternatives found in this study is consistent with previous interpretations of certainty effect and immediacy effect. That is to say, individuals assign too high weight to these alternatives (Kahneman and Tversky, 1979; Kirby and Herrnstein, 1995). Due to the high weight, individuals pay less attention to this information, and may not need deep processing, or rely on their relative evaluation and comparison with risk/future alternatives to conduct utility evaluation on certainty/immediacy alternatives. In addition, the certainty/immediacy parameter information is fixed in this study. Compared with the uncertainty/immediacy parameter, it is less difficult to recognize, and it is easier to be ignored as the experiment proceeds.

It is worth noting that the specificity of certainty/immediacy information indicates that specific parameters or situations have a greater impact on the processing of RC and IC. Therefore, future studies should focus on the comparison of these two decisions in the non-specific parameter situations.

4.4 Research significance

This paper has made several positive explorations in theory and method. On the theoretical level, it is found that RC and IC share a common process mechanism, and make a useful attempt to establish a common interpretation framework for these two decisions, which will help future research to understand the internal mechanism of human decision-making in essence, and develop a universal decision theory applicable to both RC and IC. In order to further examine the similarity and specificity of the two, future research may compare the corresponding behavioral effects based on these two decisions, such as the magnitude effect.

On the method level, this study integrated multi-dimensional data of eye-movement processes and outcomes, and used the recent eye-movement trajectory analysis method, which facilitated multi-level understanding of the differences and common mechanisms of RC and IC, and tried to overcome the deficiency of previous studies that ignored the dynamic sequence process hypothesis of information search and evaluation in decision models. Future research should be based on the holistic dynamic perspective to investigate the holistic process attributes such as the time series of decision process, and to consider the coexistence of multiple decision processes or strategies. That is to say, decision makers may adopt different decision strategies based on different experimental parameters, such as whether they are near the indifference point. Such strategies can be distinguished by analyzing indicators such as the eye-movement trajectory under different parameter conditions.

In particular, on the computational modeling level, this study used HBM fitting method to simultaneously estimate the parameters at the individual and group levels, to make a more accurate estimation of the results (Vincent, 2016), and to effectively overcome the weakness such as the limitation of data sample and the individual differences of subjects in the previous model fitting studies in this field (Green et al., 1999; Myerson, Green, Hanson, et al., 2003), which provides a more accurate answer to the question of compared with the classical discount calculation model, whether RC and IC can be better predicted by the heuristic model.

4.5 Research shortage

This study had the following shortcomings. Firstly, this study only involved the profit framework, and did not further discuss the differences and similarities of RC and IC in the loss framework and the profit-loss hybrid framework. In life, the RC and IC of the non-profit framework are ubiquitous, and the profits and losses are asymmetric: the degree of discount in the benefit field is greater than that in the loss field, and people may adopt different decision strategies in the face of profits and losses (Kahneman and Tversky, 1979; Zhang et al., 2016). Therefore, it is difficult to directly popularize the research results based on the profit framework to other frameworks, and future studies should further compare RC and IC in terms of loss or profit-loss hybrid framework.

Secondly, this study used the uniform and self-set probability or time parameters for all subjects, and ignored the equivalent conversion relationship of probability and time parameters and the individual differences in parameter settings. The values of probability and time parameters have great influences on the attributes of these two decisions. Therefore, different values of the parameters can lead to the differences in behavior and process, and the possible deviations of experimental results caused by parameter effect cannot be excluded. In addition, adopting the same set of RC and IC for different individuals may also make it difficult to eliminate the confusion on results caused by individual differences. Future research can fully consider the equivalence correspondence between probability and time, as well as individual preference differences in decision-making, so as to better control the possible impact of parameter differences on results.

Finally, based on the neural basis level, future research may use the model-based neuroimaging method to compare neuroimaging between these two decisions and explore the common neural mechanism of the two.

5 Conclusion

Taking certainty effect and immediacy effect as examples, this study compared the decision processes of RC and IC, and obtained the following findings through the evidences of behavioral, local and holistic process characteristics and model fitting. (1) In terms of basic decision rules, RC and IC share a common mechanism, neither of which follows the compensatory and alternative-based processing rules assumed by the discounting model, but is more likely to make decisions based on heuristic rules anticipated by the simple and non-compensatory model. (2) The processing complexity and depth of IC are higher than those of RC, and there are differences in the holistic dynamic eye-movement process between the two. (3) The certainty information of RC and the immediacy information of IC have specificity in process mechanism: when certainty/immediacy alternatives are excluded, the compensatory degree of individual processing is higher and attribute-based processing mode is more preferred; however, when these alternatives are included, this degree is lower and there is no dominant processing mode.

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