Eye Movement Trajectory Matching Method: A Novel Approach for Studying Decision-Making Processes

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Abstract

Eye movement trajectory matching is an emerging eye-tracking data analysis method in recent years, comprising four steps: preprocessing of fixation data, definition and coding of areas of interest, formation of eye movement trajectory strings, and calculation of similarity scores. Researchers have conducted exploratory studies on decision-making process theories and their influencing factors using the eye movement trajectory matching method, confirming the feasibility, precision, and high value of eye movement trajectory matching in the decision-making domain. Future research should further leverage eye movement trajectory matching to enhance investigations into various decision-making theories and their influencing factors, thereby revealing the cognitive processes underlying decision-making and constructing more comprehensive theoretical models of decision-making.

Full Text

Scanmatch: A Novel Method for Studying Decision-Making Processes

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Abstract

Scanmatch is an emerging method for eye movement data analysis that has gained prominence in recent years. This method comprises four steps: preprocessing of gaze data, division and encoding of regions of interest (ROIs), formation of scanpath strings, and calculation of similarity scores. Exploratory studies employing scanmatch to investigate decision-making process theories and their influencing factors have demonstrated the method' s feasibility, precision, and high value in the decision-making domain. Future research should further leverage scanmatch to strengthen investigations into various decision-making theories and their influencing factors, thereby revealing the cognitive processes underlying decisions and constructing more comprehensive theoretical models of decision-making.

Keywords: eye movement technology; scanmatch; decision-making process; new method; theoretical model

Decision-making is crucial for human survival and daily life. Although many decisions may seem trivial, their cumulative effects can be substantial (Neil, Frouke, & Matthews, 2016), such as investing in pension funds or starting a business. Over the past several decades, decision-making has been extensively studied across behavioral economics, psychology, and sociology, yielding valuable theoretical insights. However, how people actually make decisions remains a challenging question. The eye-mind hypothesis posits that there is no significant temporal lag between what the eyes fixate on and what the brain is processing (Just & Carpenter, 1980). With the advancement of eye-tracking technology, the study of decision-making processes has become increasingly feasible, emerging as a key research area in psychology and behavioral economics. Eye-tracking technology has become an essential tool for investigating complex decision-making processes that require real-time visual perception (Zhou et al., 2016).

Eye-tracking technology is used to study and analyze eye movements, which are rapid ballistic movements of the eye from one fixation point to another. Eye-tracking metrics encompass both temporal and spatial dimensions. Specifically, temporal dimensions include fixation duration, gaze duration, regression time, and total fixation time, while spatial dimensions include saccade amplitude, fixation position, fixation count, skipping rate, refixation rate, and regression count. Chinese scholars Yan Guoli et al. (2013) provided a comprehensive review of common eye movement indicators in reading research, which has been instrumental for the application and promotion of eye-tracking technology in reading and other domains. In decision-making research, studies have frequently analyzed eye movement information from both temporal and spatial perspectives (Stewart, Hermens, & Matthews, 2016; Wei & Li, 2015; Wang et al., 2016) to reveal the cognitive processes underlying decisions. However, these approaches have largely neglected the sequential and holistic nature of cognitive processes in decision-making (Day, 2010; Glöckner & Herbold, 2011; Su et al., 2013; Sun, Rao, Zhou, & Li, 2014), resulting in the loss of valuable information and hindering more precise and complete revelation of decision-making cognitive processes.

In recent years, with further development of eye movement data analysis techniques, researchers have begun exploring scanpath studies that integrate temporal and spatial dimensions. Scanpath analysis theory was first proposed by Noton and Stark to explain the representative nature of eye movement patterns (Noton & Stark, 1971). This theory hypothesizes that scanpaths are eye movement processes driven by internalized cognitive models, operating in a top-down processing manner and remaining stable across multiple exposures. Scanpaths typically reflect the sequence in which visual stimuli are processed in the brain. Noton, Stark, and subsequent researchers proposed a series of quantitative scanpath analysis methods, including string sequences, probabilistic models, and geometrical vectors, such as Markov' s (1971) Markov chains, Noton et al.' s (1971) string editing method (Levenshtein distance), and Ponsoda, Scott, and Findlay's (1995) geometrical vector measurement incorporating saccade direction. Among existing scanpath analysis methods, scanmatch is the only approach that simultaneously considers both the spatiotemporal position of visual elements and fixation duration. Proposed by Cristino, Mathôt, Theeuwes, and Gilchrist (2010), this method is based on the Needleman-Wunsch (NLW) algorithm commonly used in bioinformatics for comparing DNA sequences. In recent years, researchers both domestically and internationally have attempted to apply scanmatch to the study of cognitive processes such as decision-making, validating its precision and effectiveness (Zhou et al., 2016; Madsen, Larson, Loschky, & Rebello, 2012). However, overall, research employing this method remains scarce. In domestic decision-making research, only Professor Li Shu' s research group from the Chinese Academy of Sciences has reported findings using scanmatch. The limited adoption of this method may stem from insufficient understanding among domestic researchers regarding its computational procedures, characteristics, and underlying psychological significance. Therefore, this paper provides a detailed introduction to scanmatch based on existing research, comprehensively reviews its application progress in the decision-making domain, and discusses future research directions and application scope.

2. The Scanmatch Method

Scanmatch, proposed by Cristino et al. (2010) based on the string editing method, compares the similarity between two scanpaths through four steps: preprocessing of gaze data, division and encoding of ROIs, formation of scanpath strings, and calculation of similarity scores. The degree of similarity is measured by the similarity score to determine the differences and commonalities in cognitive processes.

Step 1: Preprocessing of Gaze Data
The first step of scanmatch involves preprocessing all participants' eye movement data by removing fixations outside regions of interest (ROIs) and those with durations shorter than 50 ms (Nuthmann & Kliegl, 2009).

Step 2: Division and Encoding of ROIs
To encode scanpaths, the visual scene must be divided into a series of non-overlapping ROIs based on research objectives, with each ROI assigned a unique character. Considering that the number of ROIs may exceed 26 (the length of the English alphabet), scanmatch typically employs dual-character encoding using lowercase and uppercase letters (e.g., aA, aB, aC, aD in Figure 1 [Figure 1: see original paper]) (Cristino et al., 2010).

Step 3: Formation of Scanpath Strings
To encode single fixation duration into the string, researchers set a base fixation duration (commonly 50 ms) based on research objectives. The character corresponding to an ROI is repeated in the string according to the ratio of the single fixation duration to the base duration. All characters are arranged in chronological order to form the scanpath string sequence. For example, the scanpath in Figure 1 can be encoded as: aAaBaBaCaDaD.

Step 4: Calculation of Similarity Scores
Cristino et al. (2010) employed the Needleman-Wunsch (NLW) algorithm, widely used in bioinformatics, to calculate the maximum similarity score between two scanpaths. First, a substitution matrix must be established, assigning alignment scores to each alignment (as shown in Figure 2 [Figure 2: see original paper]). To maximize alignment between two sequences and obtain the highest similarity score, researchers are permitted to insert gaps (spaces between characters) at any position in the sequence and align characters with gaps. The alignment score in this case is called a gap penalty. The similarity score between two scanpaths is the total alignment score of the entire sequence. However, this total alignment score is related not only to the similarity between the two scanpaths but also to the string length—the longer the length, the higher the total alignment score. For instance, under identical parameter settings, two completely identical scanpaths containing 20 characters will necessarily have a higher total alignment score than two completely identical scanpaths containing only 5 characters. In theory, however, the similarity score should be the same in both cases since the scanpaths are completely identical. To overcome the influence of string length on similarity scores, Cristino et al. (2010) proposed a normalization formula:

标准化得分替换矩阵最大对齐分数最长字符串的字符数量总对齐分数

By using this normalization formula, the highest similarity score between two scanpaths is 1, with scores closer to 1 indicating greater similarity.

The alignment scores in the substitution matrix and the gap penalty are two crucial parameters that must be set based on the relationships between scanpaths and ROIs. The closer the relationship between ROIs, the higher the alignment score, with the highest scores for alignments within the same ROI. ROI relationships can be based on either spatial position or attribute dimensions, which provides convenience for studying cognitive processes like decision-making. Another parameter requiring configuration is the gap penalty score. If the gap penalty is too high, similarity scores will be artificially low, causing scanpaths with considerable similarity to be misidentified as dissimilar. Conversely, if the gap penalty is zero or too low, similarity scores will be artificially high, causing scanpaths with minimal similarity to be misidentified as highly similar. Figure 3 [Figure 3: see original paper] illustrates two gap penalty settings and optimal solutions, allowing researchers to personalize these parameters according to their research objectives. Although the subjectivity of alignment score and gap penalty settings may cause fluctuations in the absolute magnitude of scanpath similarity scores (Eraslan, Yesilada, & Harper, 2015), the relative magnitude of similarity scores among scanpaths remains stable and comparable under identical parameter settings.

Cristino et al. developed a Matlab application—the Scanmatch Toolbox (available for download at https://seis.bristol.ac.uk/~psidg/ScanMatch/)—to facilitate implementation.

3. Applications of Scanmatch in Decision-Making Research

Scanpaths are believed to be driven by individuals' internalized cognitive models, formed through top-down cognitive processing that reflects the brain' s processing sequence and overall dynamic eye movement patterns during visual stimulus processing (Gbadamosi & Zangemeister, 2001; Noton et al., 1971; Underwood, Humphrey, & Foulsham, 2008). This top-down processing approach determines that scanpaths remain relatively stable when people employ the same decision strategy, while substantially different scanpaths emerge when different strategies are used. By calculating and comparing similarity scores between scanpaths in decision tasks, researchers can reveal the theoretical models governing decision processes and identify relevant influencing factors.

3.1 Research on Decision-Making Theories

The field of behavioral decision-making has long debated relevant theoretical models, primarily concerning two competing theoretical frameworks. The first originates from models of unbounded rationality, such as expected value theory (Pascal, 1670) and probability discounting theories centered on prospect theory (Kahneman & Tversky, 1979). These models propose that decision-making is an option-based, compensatory strategy where individuals integrate probability and outcome dimensions to compare utility values and select the optimal outcome. The second framework comprises non-discounting models based on bounded rationality, such as the priority heuristic (Brandstätter, Gigerenzer, & Hertwig, 2006) and the equate-to-differentiate model (Li, 2004). These models suggest that decision-making is an attribute-based, non-compensatory strategy where individuals compare only specific dimensions of options to make decisions.

To resolve this theoretical controversy, researchers have recently begun exploring scanmatch to validate decision-making theoretical models. Zhou (2014) initially employed an algorithm similar to scanmatch to investigate strategies (compensatory or non-compensatory) used by participants during decision-making. However, this study utilized mouse-tracking technology rather than eye-tracking (all information except the mouse position was masked) to obtain decision process sequences. Participants were asked to sequentially use compensatory and non-compensatory strategies to choose among three hypothetical apartments. Results revealed that decision process sequences generated using compensatory strategies showed higher similarity to sequences from free decision-making compared to non-compensatory strategies. Although this study did not employ eye-tracking technology, it utilized the similarity scoring algorithm from scanmatch, providing algorithmic support for applying scanmatch to decision-making theory research.

Subsequently, researchers formally applied scanmatch to decision-making theory research, yielding a series of valuable findings. Zhou et al. (2016) first used scanmatch to explore decision strategies employed in risky decision-making. This study analyzed three sets of experimental data, each comprising a baseline condition and an experimental condition. Baseline conditions included proportional decision tasks, outcome-matched risky decision tasks, and outcome-multiple-application risky decision tasks, while experimental conditions included probability decision tasks, outcome-crossed risky decision tasks, and outcome-single-application risky decision tasks. Scanmatch was used to calculate within-condition and between-condition similarity scores. By comparing these scores, researchers determined whether decision processes differed between conditions, thereby validating decision strategies in risky decision-making. The underlying logic was that when risky decision outcomes were presented in matched or crossed formats, if within-condition and between-condition similarity scores showed no significant differences, risky decision-making would be unaffected by outcome presentation format and would be based on option-based compensatory strategies. Conversely, significant differences would indicate attribute-based non-compensatory strategies. Proportional tasks and outcome-multiple-application risky decision tasks have been confirmed as compensatory strategies (Zhang, Rao, Liang, Zhou, & Li, 2014; Sun, Rao, Zhou, & Li, 2014). Results showed that within-condition similarity scores were significantly higher than between-condition scores across all three experiments, indicating substantial differences in scanpaths between baseline and experimental conditions. This supported the conclusion that risky decision-making (outcome-single-application) employs attribute-based, non-compensatory strategies. Additionally, researchers examined typical trials from each condition (trials with the highest average similarity scores to all other trials) and found substantial differences in scanpath patterns across conditions, further validating these conclusions. These findings align with existing decision-making theory research (Su et al., 2013; Sun et al., 2014; Mathôt, Cristino, Gilchrist, & Theeuwes, 2012). Thus, scanmatch proves to be a reliable and effective new method for studying decision-making theories.

Zhou Lei et al. (2018) further utilized scanmatch to compare cognitive processes between risky and intertemporal decision-making. Results showed that regardless of whether certain/immediate options were included, similarity scores between risky and intertemporal decision tasks were significantly lower than within-task similarity scores. Further examination of typical trials revealed that risky decision-making exhibited more attribute-based saccades, while intertemporal decision-making showed no dominant dimension-based or option-based eye movement patterns. This suggests that risky and intertemporal decision-making may employ different strategies, with intertemporal decision strategies being more complex. This study innovatively applied scanmatch to provide new evidence for comparing cognitive processes between risky and intertemporal decision-making, representing a novel exploration of intertemporal decision-making theory.

In summary, scanmatch demonstrates good applicability in decision-making theory research. Future studies could employ scanmatch to investigate cognitive processes across various decision types, including intertemporal, ambiguous, and social decisions, and conduct detailed examinations of non-compensatory strategies such as heuristics and equate-to-differentiate in risky decision-making. For instance, within a "forced-choice rule experience"paradigm, participants could be asked to perform weighted-sum forced-choice tasks, heuristic forced-choice tasks, and free decision tasks. Scanmatch could then calculate and compare similarity scores between the two forced-choice tasks and the free decision task. Higher similarity scores would indicate that free decision-making is more likely to follow the strategy employed in that forced-choice task. Additionally, another important method for validating decision theories involves calculating typical trials within each task using scanmatch and intuitively observing their scanpath patterns to identify employed strategies. For example, the priority heuristic is characterized by decision-makers making more fixations on minimum outcomes. By comparing typical trial scanpath patterns with this characteristic, researchers can intuitively determine whether participants adopted this strategy.

3.2 Research on Decision-Making Influencing Factors

Since Cristino (2010) proposed scanmatch, subsequent researchers have begun using this method to explore influencing factors in decision-making. Zhou (2014) used scanmatch to investigate the impact of time pressure on decision-making processes. Participants were asked to make decisions about movies to watch under six time conditions (6s, 12s, 18s, 24s, 30s, and 36s), with 36s serving as the baseline. Results revealed that closer decision times yielded higher scanpath similarity scores, with the greatest differences observed between 12s and 6s conditions. This suggests that under excessive time pressure, decision-makers become overly stressed, causing them to forget their normal decision strategies. Similarly, Dewhurst et al. (2012) found that task difficulty affected decision strategies and scanpaths, with similarity scores decreasing as task difficulty increased, generating more diverse decision strategies and scanpaths.

Beyond external factors, scanmatch has also been used to explain how internal individual factors influence decision-making. Khedher, Jraidi, and Frasson

(2018) employed scanmatch to study medical diagnostic decision-making in medical students. They first constructed a correct reasoning process for diagnosing amnesia and then compared it with students' actual reasoning scanpaths. Results showed that stronger reasoning ability correlated with higher similarity scores and more accurate diagnostic decisions. However, this study considered ROI fixation order as the primary factor and therefore did not incorporate single fixation duration when calculating similarity scores.

More recently, Król and Król (2019) exploratorily applied a string editing method similar to scanmatch in a financial investment feedback task to improve economic decision quality. They compared participants' free decision scanpaths with correct decision scanpaths and provided feedback on similarity scores. Results showed that through feedback learning, decision-makers gradually learned correct decision scanpaths, leading to improved decisions. However, this string editing method considered only sequential information from eye movement data, not fixation duration. It can be inferred that providing feedback based on scanmatch-calculated similarity scores or directly presenting typical trial scanpaths from correct decisions could help decision-makers more completely understand the attentional processes and processing depth of correct decisions, mastering effective pathways and key steps for making correct decisions. This approach would be particularly beneficial. However, this method' s prerequisite is that researchers must first obtain typical trial scanpaths from correct decisions. Therefore, this decision-quality improvement approach may be suitable for procedural decisions with fixed steps and processes but not for non-procedural decisions requiring innovative thinking, as these may lack fixed pathways to correct outcomes. Additionally, such methods may be more applicable to novices by providing basic pathways to correct decisions, whereas expert decision-makers may not need guidance from typical trials.

In conclusion, widespread application of scanmatch in decision-making research will enable researchers to understand not only what decisions are made but also why they are made, offering high potential for revealing the cognitive mechanisms through which variables such as framing effects, psychological distance, and emotion influence decision processes. Notably, scanmatch calculates similarity scores between two scanpaths, typically involving comparisons between two levels of the same factor. Therefore, when a factor has only two levels, similarity scores can be calculated directly, with scores closer to 1 indicating more similar decision processes. When a factor has more than two levels, researchers can set one level (e.g., neutral emotion in emotional factors) as the baseline condition and calculate similarity scores between the baseline and other conditions (e.g., negative and positive emotions) to explore differential effects of each factor level on decision processes.

4. Summary and Outlook

In summary, scanmatch can accurately and effectively reveal attentional processes and cognitive mechanisms in complex decision-making, holding significant importance for refining theoretical models and exploring influencing factors. This is likely attributable to three distinctive features of scanmatch.

First, scanmatch’ s greatest advantage may be its ability to identify typical trials for each task. By intuitively observing scanpaths from typical trials, researchers can grasp holistic, dynamic decision-making processes. Analyzing decisions from a holistic dynamic perspective enables more concrete, intuitive, and comprehensive understanding of thinking processes, employed strategies, and key divergences in decision-making, which is crucial for revealing cognitive processes underlying different decision strategies. Previous eye movement and decision-making research predominantly utilized local eye movement data, lacking analysis of overall scanpaths. Some studies described holistic cognitive processes by plotting multiple scanpath diagrams (Chen, Zhou, Han, & An, 2013; Sperati, 2003) and scanpath coordinates (Chen & Zheng, 2014). However, typical trial scanpath patterns can completely describe decision-making cognitive processes with a single trajectory, offering greater specificity, simplicity, and representativeness.

Second, when evaluating similarity between two fixation sequences, scanmatch considers single fixation duration within ROIs, whereas other quantitative scanpath analysis methods ignore this factor. In fact, fixation duration is significantly related to processing depth and difficulty (Velichkovsky, Rothert, Kopf, Dornhöfer, & Joos, 2002; Follet, Meur, & Baccino, 2011), particularly in high-level cognitive processes like decision-making that require deep information processing. Therefore, scanmatch is most appropriate for researchers seeking to reveal cognitive processes in decision-making. Comparative studies on scanmatch’ s precision have found a correlation of 0.74 between representative scanpaths (those with minimum total distance to all other scanpaths) derived from scanmatch and string editing distance methods. Further multidimensional scaling (MDS) analysis of optimal and suboptimal representative scanpaths from both methods revealed higher similarity between scanmatch-derived scanpaths, indicating greater precision compared to string editing distance methods (Takeuchi & Matsuda, 2012).

Third, another advantage of scanmatch is that it allows researchers to classify ROIs based on any dimension—cognitive, perceptual, or task-related—according to research needs, and set alignment scores between ROIs in the substitution matrix accordingly. This is extremely important for decision-making research because logical relationships between ROIs in decision tasks often extend beyond spatial dimensions to attribute dimensions such as value, probability, or proportion. These ROIs may be far apart spatially but should receive high alignment scores in the substitution matrix due to belonging to the same attribute. For example, in risky decision tasks, researchers can set high alignment scores (e.g., 5) between ROIs within the same option that are spatially close, and similarly set high scores (e.g., 5) between ROIs that are spatially distant but belong to the same attribute (probability or value), while setting low scores (e.g., -5) between ROIs that are both spatially distant and belong to different attributes.

Although scanmatch is a valuable research tool for studying cognitive processes like decision-making, its application in decision-making research remains limited. Future researchers should comprehensively consider this method' s advantages and disadvantages, designing experiments that maximize strengths and minimize weaknesses to conduct more in-depth research in the following areas.

First, although existing decision-making theoretical models make identical predictions about decision outcomes (Johnson, Schulte-Mecklenbeck, & Willemsen, 2008), they exhibit substantial differences and even contradictions in their assumptions about decision processes. As discussed above, prospect theory (Kahneman & Tversky, 1979) can well fit risky decision outcomes and appears to be a very correct theory (Glöckner & Herbold, 2011; Suter, Pachur, & Hertwig, 2016). However, numerous studies, including those using scanmatch, indicate that decision processes do not involve weighted summation as prospect theory assumes (Zhou et al., 2016; Zhou, Zhang, Li, & Liang, 2018). Beyond risky decision-making, theoretical models in intertemporal, ambiguous, and social decision-making domains also face numerous controversies. Given that existing research methods have failed to reach consistent conclusions, scanmatch may be an important approach for further resolving these theoretical disputes. Future research should strengthen validation studies using scanmatch across various decision-making theoretical models to construct more complete theoretical frameworks.

Second, decision-making is a complex cognitive process (Rogers, 2011) that relies on numerous control functions, including selection, inhibition, working memory, emotion, evaluation, feedback, and executive functions. Therefore, changes in any control function during decision-making will alter decision behavior. Many studies have found that psychological distance, gain/loss frames, individual traits, and other factors influence decision-making, with researchers proposing construal level theory, emotion maintenance hypotheses, and other theories to explain these effects (Trope & Liberman, 2010; Isen & Patrick, 1983). However, most of these theories lack support from decision process data. Some researchers have explored how relevant variables affect brain regions such as the prefrontal cortex and anterior cingulate cortex during decision-making from a cognitive neuroscience perspective (Gleichgerrcht, Ibáñez, Roca, Torralva, & Manes, 2010) to reveal underlying neurocognitive mechanisms. However, decision tasks often involve complex visual information, and neuroscientific methods cannot precisely locate information acquisition in space, time, and sequence. Future research could combine cognitive neuroscience techniques with eye-tracking technology, using scanmatch to synchronize temporal, spatial, and sequential information with neuroscientific data to further reveal cognitive processes and influencing factors in decision-making.

Third, scanmatch also holds high application value in experimental design and validity testing. In behavioral experiments, participants often fail to complete decision tasks as instructed due to various reasons, contaminating research data and distorting results. Existing methods struggle to precisely filter out such invalid data, whereas scanmatch's similarity scores and typical trial scanpaths can diagnose invalid decisions where participants failed to follow instructions. This method can effectively filter invalid data when participants employ disadvantageous or incorrect strategies or make decisions while fatigued or under excessive cognitive load. In a recent study, Schoemann, Schulte-Mecklenbeck, Renkewitz, and Scherbaum (2019) exploratorily used scanpaths to detect whether participants made decisions according to specified strategies. Thus, future research should strengthen scanmatch' s application in improving the validity of decision-making experiments to ensure data accuracy and reliability.

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Note: Figure translations are in progress. See original paper for figures.

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