Eye Movement Monitoring as a Process Tracing Methodology in Decision Making Research

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Over the past half century, research on human decision making has expanded from a purely behaviorist approach that focuses on decision outcomes, to include a more cognitive approach that focuses on the decision processes that occur prior to the response. This newer approach, known as process tracing, has employed various methods, such as verbal protocols, information search displays, and eye movement monitoring, to identify and track psychological events that occur prior to the response (such as cognitive states, stages, or processes). In the present article, we review empirical studies that have employed eye movement monitoring as a process tracing method in decision making research, and we examine the potential of eye movement monitoring as a process tracing methodology. We also present an experiment that further illustrates the experimental manipulations and analysis techniques that are possible with modern eye tracking technology. In this experiment, a gaze-contingent display was used to manipulate stimulus exposure during decision making, which allowed us to test a specific hypothesis about the role of eye movements in preference decisions (the Gaze Cascade model; Shimojo, Simion, Shimojo, & Scheier, 2003). The results of the experiment did not confirm the predictions of the Gaze Cascade model, but instead support the idea that eye movements in these decisions reflect the screening and evaluation of decision alternatives. In summary, we argue that eye movement monitoring is a valuable tool for capturing decision makers’ information search behaviors, and that modern eye tracking technology is highly compatible with other process tracing methods such as retrospective verbal protocols and neuroimaging techniques, and hence it is poised to be an integral part of the next wave of decision research.

Keywords: eye movements, process tracing, decision making

Early research in decision making focused on explaining and predicting decision outcomes, such as choices and judgments. This approach, known as the structural approach, produces statistical models that account for decision makers’ responses (outcomes) as a function of the stimulus information and parameters of the decision (inputs). While this approach has been quite successful in probing the strategies that decision makers apply, the modeling of outcomes cannot identify different stages of the decision process, or changes in the decision strategy that might occur prior to the final response. To shed light on these aspects of decision making, researchers have sought ways to observe more directly the cognitive processes that occur prior to the final behavioral response. This approach, which was originally applied to research on problem solving, is known as process tracing (for discussion regarding these two approaches, see Abelson & Levi, 1985; Billings & Marcus, 1983; Einhorn, Kleinmuntz, & Kleinmuntz, 1979; Harte & Koele, 1995; Payne, Braunitz, & Carrol, 1978; Svenson, 1979, 1996).

There are several methods of process tracing that have been applied in decision making research, primarily involving the use of verbal protocol techniques or information search display paradigms (for reviews see Ford, Schmitt, Schechtman, Hults, & Doherty, 1989; Riedl,
Brandstätter, & Roithmayr, 2008). The main goal of the present article is to evaluate and illustrate the potential utility of eye movement monitoring as a process tracing method. Accordingly, we begin by briefly introducing and contrasting several methods of process tracing. We then review research that employed eye movement recordings to study processes underlying decision making. Finally, we report an experiment that demonstrates the unique possibilities afforded by eye movement monitoring. In particular, we tested a hypothesis about the role of eye movements in preference decisions (the Gaze Cascade model; Shimojo et al., 2003; Simion & Shimojo, 2006, 2007). Using a sophisticated method of updating the display based on eye position (gaze-contingent display), stimulus exposure was manipulated during ongoing decisions, allowing for a direct test of the predictions of the model proposed by Shimojo and colleagues. In addition, the present study demonstrates several new techniques for analyzing eye movement data in the context of multialternative decisions.

**Process Tracing and Monitoring Information Search**

Early process tracing research employed verbal protocols in an attempt to observe the cognitive processes that occur during decision making. Verbal protocols involve having the decision maker describe what they are thinking or doing (i.e., “think aloud”) while making their decision (concurrent verbal protocol), or having them recall their decision process after the decision has been made (retrospective verbal protocol). While the verbal protocol methodology has been shown to provide information regarding the sequence of information sampled, and can often suggest the decision strategy that is employed by participants, this method has several potential shortcomings. Concurrent verbalization is effectively a secondary task that the decision maker conducts in parallel with the ongoing decision, the burden of which has been shown to reduce decision accuracy (Russo, Johnson, & Stephens, 1989). Retrospective verbal protocols rely on the decision maker having accurate memory for the decision process as it unfolded. However, it has been demonstrated that decision makers’ retrospective protocols reflect substantial forgetting and confabulation (Russo et al., 1989). To corroborate and expand the information revealed by verbal reports, methods have been developed to more directly observe the patterns of information search that are employed by decision makers.

The traditional method of monitoring information search is through the use of information search displays. In these paradigms (also referred to as information display boards, information display matrices, or computer process tracing), decision makers are presented with a matrix of stimulus information (alternatives by column and attributes by row, or vice versa) and they are tasked with making a decision about the alternatives according to some decision rule. Of note, the information search display paradigm constrains the way in which the decision maker samples information from the display. The information in each cell in the matrix is hidden. Decision makers must access cells individually, and the displayed information is concealed when the decision maker selects another cell. In this way the decision maker’s pattern of information search is made explicit. A variety of measures of information search can be derived from this method, such as the depth of search, variability of search, and pattern of search (see Riedl et al., 2008 for a review of these measures). These measures can be used to infer the presence of certain decision strategies, and can detect transitions between different stages of processing (Ball, 1997; Billings & Marcus, 1983; Levin, Huneke, & Jasper, 2000; Payne, 1976; Payne, Bettman, & Johnson, 1993).

In the early versions of this paradigm, the information in each cell was written on a card in an envelope, and the decision maker would remove, view, and then replace each card individually. Computerized versions of this paradigm present the information matrix on a computer screen, and participants use a pointing device (often a mouse) to reveal individual cells in the matrix. Computerized versions of the paradigm offer obvious advantages in both ease of use for the decision maker, and in precision of the measurements obtained. However, all versions of this method suffer from a potential shortcoming. In these paradigms the decision maker must execute a deliberate manual act in order to sample each piece of information (i.e., select it by
In natural decision situations in which a decision maker is presented with multiple alternatives, decision makers sample information from those alternatives by directing their gaze to them. In general, people make rapid eye movements (called saccades) roughly three to four times each second. The periods between saccades where the eye is relatively still, and visual information is extracted, are known as fixations (for a review of eye movement measures, see Rayner, 1998, 2009). Eye movements are considerably faster than movements of the hand, and they require less deliberate effort to execute. This difference has important implications for process tracing in decision making because it has been argued that effort, and basic information processing limitations such as memory, play a significant role in the way that decisions are made (Payne et al., 1993), and hence any method of process tracing that produces artificial demands of these kind may actually alter the decision process.

This issue was investigated by Lohse and Johnson (1996), in a direct comparison of the information search display and eye movement monitoring process tracing methods (specifically, comparing a computerized information search display tool called Mouselab, and an eye movement monitoring system called Eyegaze). Consistent with prior findings (Russo, 1978; van Raaij, 1977), they found significant differences in the process data obtained from these two process tracing methodologies. In particular, Lohse and Johnson found that the information search display paradigm produced longer total time per decision, longer time per information acquisition, lower rate of reacquisition, more information searched, and reduced decision accuracy. Furthermore, these differences became more pronounced in decisions that are more complex (i.e., more alternatives or attributes). Lohse and Johnson concluded that compared with eye movement monitoring, the information search display methodology imposes greater demands in effort and working memory.

These findings strongly advocate the use of eye movement recordings as a process tracing measure (but see Reisen, Hoffrage, & Mast, 2008, for a critique). In addition, there are several other reasons why eye movement monitoring may be desirable over other methods of monitoring information search. Of note, unlike information search displays that are primarily sensitive to deliberate information sampling, eye movement recordings capture a broader range of information sampling acts, which are executed with or without conscious awareness (e.g., eye movements that are elicited exogenously). In addition, eye movement recordings might be very useful in supplementing and disambiguating concurrent verbal reports or by serving as powerful cues for retrospective verbal protocols. For example, in a recent study, Eger, Ball, Stevens, and Dodd (2007) found that eye movements collected passively during ongoing performance were particularly informative when replayed to participants as cues during a retrospective verbal protocol (eye movement-cued retrospective verbal protocol; see also Hansen, 1991; van Gog, Paas, van Merriënboer, & Witte, 2005). This combination of methods has also been successful in the context of usability research, where the pattern of eye movements can yield insight into the processing steps taken by users (for a review of eye tracking in the field of usability see Ehmke & Wilson, 2007; for a more general review of eye tracking in applied contexts, see Duchowski, 2002).

One caveat in using eye tracking as a process tracing measure must be acknowledged. The eye tracking methodology assumes that the decision maker’s attention is focused at the point of fixation, though research in visual attention has shown that people are able to direct their attention covertly to areas of the visual field away from their point of gaze (Posner, Snyder, & Davison, 1980). However, during natural viewing, attention and eye movements are tightly coupled: the focus of attention tends to shift to a new location just prior to a shift in gaze to that location and consequently the spatial distribution of eye fixations is a good indirect measure of the distribution of visual attention (for a review see Hoffman, 1998). Furthermore, the link between the eye movement and attentional systems is supported by neurophysiological data (e.g., Goldberg & Wurtz, 1972; Kustov & Robinson, 1996; Mohler & Wurtz, 1976; Wurtz & Mohler, 1976) and work with neuropsychological populations such as neglect patients (e.g., Johnston & Diller, 1986; Walker & Young, 1996). Hence, during decision making tasks where participants are allowed to freely view the decision information, eye movements may be generally considered to
provide a valid measure of the spatial distribution of attention.

In the past, the use of eye tracking in process tracing has been dissuaded by the cost of the equipment, the relatively low fidelity of the data obtained, and the strict requirements for head-stabilization during recording (e.g., a bite-bar). Current video-based eye tracking technology allows for head-free eye movement monitoring while participants view a computer or a projection screen, conditions that are ideal for observing computer-based decisions (e.g., online shopping). Also, lightweight portable eye tracking equipment that is mounted on goggles or eye glass frames is available, allowing for the recording of eye movements while people make decisions in natural everyday decision environments (e.g., store shopping). In addition the spatial and temporal resolution as well as the accuracy of present day eye trackers is vastly superior to that of their predecessors. These improvements in eye tracking technology allow for the possibility of a real time manipulation of the stimulus display as a function of the participant’s gaze location. This technique, known as gaze-contingent display (McConkie & Rayner, 1975; Rayner, 1975), allows for a variety of experimental manipulations (as is illustrated in the present experiment). Hence, eye tracking technology has advanced to the point where it can yield high fidelity process tracing data with minimal intrusion upon the natural behavior of the decision maker.

**Process Tracing With Eye Movement Recordings**

Prior research may be coarsely divided according to the approach used in analyzing the eye movement record. Because of limitations in the eye tracking technology available at the time, early studies tended to focus on the spatial distribution of eye movements (e.g., where the decision maker looks; the order in which information is sampled). Advances in eye tracking technology (in particular, increases in the rate at which gaze position is sampled) have allowed for more sophisticated analyses of the temporal information contained in the eye movement record (e.g., the duration of individual fixations).

Russo and colleagues (Russo, 1978; Russo & Dosher, 1983; Russo & Leclerc, 1994; Russo & Rosen, 1975) pioneered the use of eye movement monitoring as a process tracing method. These early eye movement studies attempted to identify natural indices of decision processes in the eye movement record. For example, Russo and Rosen (1975) observed that certain patterns of gaze transitions were a prominent feature of the eye movement record while participants chose one of six cars (where each car was described by three attributes). Paired comparisons were identified as sequences in the eye movement record where participants looked back and forth between two alternatives (where the sequence A-B-A was classified as a “weak” pair and the sequence A-B-A-B was classified as a “strong” pair). Participants’ verbal reports corroborated the claim that such transition sequences in fact reflected paired comparisons. Russo and Rosen found that these sequences tended to involve alternatives that were similar (i.e., sharing attributes). In addition, alternatives involved in paired comparisons tended have higher subjective utility (as revealed by a separate subjective rating task in which participants rated alternatives on a continuum between “worst” and “best”), and were refixated more frequently than alternatives that were not involved in paired comparisons. Together these findings suggest that decision makers may effectively narrow a multialternative decision to a decision among a smaller set of competitive alternatives. However, in follow-up analyses regarding the relative utility of the alternatives within each pair, it was not possible to determine the exact nature of the processing steps taking place in paired comparisons (such as evaluation vs. elimination). Hence while the eye movement record was useful in revealing the set of decision alternatives that are actively being processed, other sources of information might be required to identify the actual (cognitive) processing steps that take place.

Russo and Leclerc (1994) analyzed the sequence of eye fixations in order to identify different stages of the decision process. Eye movements were recorded through a one-way mirror while participants made consumer decisions among groups of up to 16 everyday household items placed on a mock store shelf. The decision period was separated into stages based on the first and last time that the participant’s gaze refixated a decision alternative. Specifically, the first stage was identified as the period
prior to the first refixation on an alternative. The first refixation marked the onset of the intermediate (second) stage. The termination of the second stage, and the onset of the third stage of processing, was identified by the first refixation on an alternative when counting back from the response (i.e., identical to the method for identifying the first stage, but looking at the sequence of fixations in reverse). Russo and Leclerc hypothesized that the first stage might involve either a screening process, where decision alternatives are processed selectively based on their relevance and inferior alternatives are excluded from further processing, or else an orientation process where alternatives are initially surveyed prior to further processing. The second stage was linked to an evaluative stage of processing where competitive alternatives are compared and the majority of the decision “work” takes place. The final segment of the decision time course was described as a stage involving a review of competitive alternatives just prior to the final response. Aspects of this stage structure have been corroborated by research using the information search display methodology (Wedell & Senter, 1997).

Measurements of the spatial distribution of eye movements have also been used to derive measures that are analogous to those obtained from information search displays, such as the pattern of information search, variability of information search, and depth of information search (Day, Lin, Huang, & Chuang, 2009; Lohse & Johnson, 1996; Pieters & Warlop, 1999; Reisen et al., 2008; Rosen & Rosenkotter, 1976; Russo & Dosher, 1983; Selart, Kuvaas, Boe, & Takeamura, 2006). Specifically, to index the pattern of information search (developed by Payne, 1976), researchers compare the number of alternative-wise gaze transitions (i.e., moving one’s gaze from one attribute to another within a single alternative) and the number of attribute-wise gaze transitions (i.e., moving one’s gaze from one attribute in a decision alternative to the same attribute in another alternative). In particular, these measures can describe the extent to which the participant’s decision strategy involves the holistic encoding and evaluation of decision alternatives. When confronted with a complex decision scenario (e.g., with many alternatives and many attributes), limitations in information processing capacity may prevent decision makers from encoding each decision alternative holistically along all attributes. Instead, participants may adopt heuristic strategies that result in changes in the pattern of search, depth of search, and variability of search (for a review, see Payne et al., 1993). Specifically, increased complexity brings about a shift toward an attribute-wise search pattern, where alternatives are processed along particular attributes (e.g., the most important attributes). In addition, participants may ignore some decision information altogether (reduced depth of search), or process some alternatives or attributes more extensively than others (increased variability of search).

In general, measures of search pattern, depth of search, and variability of search, obtained from eye movement recordings have provided convergent evidence to prior findings using information search displays. However, some differences between these two process tracing methodologies have been documented. Lohse and Johnson (1996) reported that compared with eye movement monitoring, information search displays induced a more alternative-wise search, with greater depth (i.e., more information sampled), but less variability. In contrast, Reisen et al. (2008) found the information search displays produced a more attribute-wise search, with less variability, but with comparable depth of search to the eye movement monitoring method. Further research is clearly required to tease apart the differences between these two methods of monitoring information search.

Since the first wave of research in this domain, there has been an increasing trend toward deriving estimates of the temporal characteristics of eye movements during decision making (e.g., fixation duration). For example, Pieters and Warlop (1999) monitored participants’ eye movements while they chose one of six different brands within a single product category (rice, shampoo, canned soup, or salad dressing). The six alternatives for each trial were displayed simultaneously on a computer screen. One goal was to test the commonly held belief regarding consumer decisions that products receiving more attention are more likely to be chosen. In addition, Pieters and Warlop asked whether two factors external to the decision would affect the pattern of eye movements observed during the decision: the motivation of the decision maker (decision rewarded or not), and
time constraints imposed upon the decision maker (7 second time limit or unlimited). Piers and Warlop obtained an estimate of the duration of individual eye fixations, and they found a bias toward the item that was chosen, where participants spent more time fixating items that were chosen compared with items that were not. This was driven by longer, and more frequent, fixations on the chosen item. In addition, while the manipulations of task motivation and of time constraints did have an impact on eye movements overall (e.g., fixation durations), they did not have a significant effect on the bias in eye movements toward the item that was chosen.

More recently, advances in eye tracking technology have allowed for precise analysis of the temporal information contained in the eye movement record. The rate of sampling of gaze position has improved dramatically, allowing for precise estimates of the duration that stimulus information is viewed. This has brought about an increase in the application of eye tracking to decision making (Bee, Prendinger, André, & Ishizuka, 2006; Glaholt & Reingold, 2009a, 2009b; Glaholt, Wu, & Reingold, 2009, 2010; Schotter, Berry, McKenzie, & Rayner, 2010; Shimojo et al., 2003; Simion & Shimojo, 2006, 2007; Sutterlin, Brunner, & Opwis, 2008) as well as associated areas including problem solving and reasoning (Ball, Lucas, Miles, & Gale, 2003; Ball, Phillips, Wade, & Quayle, 2006; Ellis, Glaholt, & Reingold, in press), categorization (Rehder & Hoffman, 2005a, 2005b); and visual marketing and advertising (Goldberg, Probart, & Zak, 1999; Pieters, Rosenbergen, & Wedel, 1999; Pieters & Wedel, 2004, 2007; Radach, Lemmer, Vorstius, Heller, & Radach, 2003; Rayner, Miller, & Rotello, 2008; Rayner, Rotello, Stewart, Keir, & Duffy, 2001; Wedel & Pieters, 2000; Wedel, Pieters, & Liechty, 2008; for a review, see Wedel & Pieters, 2008). These recent studies have introduced several new methods of analyzing the temporal information contained in the eye movement record.

For example, Shimojo et al. (2003) introduced an analysis of the decision time course prior to the response, known as “gaze likelihood analysis.” This analysis plots, for each time bin over a period prior to the response (where each bin spans a certain number of samples of gaze position), the likelihood that observers’ gaze was directed toward the stimulus that was eventually chosen (Figure 3a and b for an illustration of gaze likelihood analysis). Shimojo et al. (2003) monitored gaze position while participants made two-alternative forced choice (2-AFC) preference decisions between pairs of faces that were presented simultaneously on screen. Gaze likelihood analysis revealed that over the period just prior to the response there was a progressively increasing bias in the likelihood that observers’ gaze was directed toward the chosen stimulus. This bias was dubbed ‘the gaze cascade effect,’ and led to the formulation of a specific hypothesis about the role of eye movements in preference decisions (the Gaze Cascade model; discussed later in the context of our experiment).

Simion and Shimojo (2006, 2007) considered a potential hurdle for interpreting the gaze cascade effect that is of general interest to process tracing research in decision making. They were concerned that the effect might partly reflect a tendency to direct gaze to the chosen item at the point of decision, or even after the decision had been (cognitively) resolved. Such a bias might occur while the response is being held in memory, or while the motor response is being programmed. Indeed, related issues were considered by Russo and Leclerc (1994), who identified processing events that are very near to the response, including review/verification just prior to the response where the decision was nearly complete, or additional verification following the response (e.g., ‘second-guessing’). Thus it is of general interest for process tracing research to dissociate components of the decision process that occur over the duration of the decision and prior to the response, reflecting the extraction and evaluation of information from decision alternatives, and those that are tied to the announcement of the decision outcome. This issue is relevant for all process tracing methods that monitor information search, but it is particularly important to consider in the context of eye movement recordings, as one might expect there to be a significant interval where the decision has been made, and the eye is still “waiting” for another effector (such as the hand) to announce the response (see Ball et al. (2003), for a related discussion in the context of research on problem solving and reasoning).

To rule out response-related explanations for the gaze cascade effect, Simion and Shimojo...
(2006) employed a sophisticated experimental manipulation that has only recently become possible with high fidelity eye movement monitoring. This technique, known as the gaze-contingent window, updates the display in real time such that there is a window that is continuously centered on the viewer’s point of gaze. Stimulus information is visible inside the window and it is masked outside the window, which restricts the viewer to processing stimulus information within the central region of vision (for a review see Rayner, 1998, 2009; for a review of applied uses of gaze-contingent window methodology see also Reingold, Loschky, McConkie, & Stampe, 2003). In the context of decision making research, the gaze-contingent window can be used to force the decision maker to process individual decision alternatives one at a time, much like the deliberate sampling that occurs with information search displays. Simion and Shimojo (2006) expected that this mode of viewing would substantially lengthen the decision time course, and that if the bias could be demonstrated a sufficient amount of time in advance of the response, then it would be possible to rule out response-related explanations for the effect. Indeed, they found that gaze-contingent window viewing mode greatly increased decision times compared with decisions made under conditions of free viewing, and that in the gaze-contingent mode the gaze cascade effect began several seconds prior to the response, compared with ~1.5 seconds prior to the response in free viewing. Based on this finding, Simion and Shimojo argued that the bias in gaze likelihood could not be attributed to response-related factors alone, but rather was likely related to the ongoing decision process.

However, Glaholt and Reingold (2009a) observed that in both two-alternative and eight-alternative forced-choice decisions (under preference and nonpreference decision instructions), there was a strong and significant tendency for the chosen alternative to be the last alternative viewed before the response. Based on this finding, it became clear that in order to rule out response-related explanations for any observed gaze bias, it was insufficient to demonstrate a bias a certain amount of time before the response, but rather it was necessary at least to show a bias prior to the last alternative viewed during the decision. This prompted the development of a novel analysis, known as ‘dwell sequence analysis’, which identifies the sequence of dwells that occur over the course of the decision, where a dwell is a run of consecutive fixations on a decision alternative (similar to an individual “look” in an information search display). Of note, the dwell sequence analysis distinguishes between how often gaze is directed to a decision alternative and how long gaze dwells on a decision alternative, two components that are confounded in gaze likelihood analysis.

Glaholt and Reingold (2009a) found that two-alternative decisions (under both preference and nonpreference decision instructions; Figure 1a) were composed of very few dwells, making it difficult to depict the decision time course, and even harder to rule out response related explanations for observed biases. In addition, Glaholt and Reingold (2009a) examined the effect of a gaze-contingent window manipulation on 2-AFC decisions (see Figure 1b) and replicated the finding of Simion and Shimojo (2006) of a gaze bias that appeared much earlier in the decision time course. However, it was found that rather than extending the decision time course in terms of the number of dwells, the gaze-contingent window manipulation merely extended the length of individual dwells.

Hence even under these conditions it was difficult to rule out response-related explanations for the gaze bias effect. In search of a decision task that would produce a longer dwell sequence, Glaholt and Reingold (2009a) examined eight-alternative decisions (8-AFC; Figure 1c). The 8-AFC decisions were found to be composed of an extended sequence of dwells, over which two separate choice-related gaze biases were manifest (we use “gaze bias” generally to refer to the finding of an eye movement measure that shows differentiation between the chosen item and items that were not chosen). Specifically, the last few dwells in a decision tended to have a high probability of being directed toward the chosen item (a bias in dwell frequency). In addition, dwells on the chosen item were longer than dwells on other items, from the very first dwell and throughout the decision period (a bias in dwell duration). Of note, both of these biases were manifest well in advance of the response, in temporal distance, but more importantly in the unit of dwells. This constitutes clear evidence that these biases cannot be accounted for by response-related explanations, and instead
they likely reflect aspects of the decision process itself.

The dwell duration bias and the dwell frequency bias that emerged from this analysis also exhibited certain dissociations that suggest different processing roles. For one, the dwell duration bias was present from the beginning of the decision period while the dwell frequency bias that emerged from this analysis also...
bias occurred only toward the end of the decision period. As such, these biases might map onto different stages of the decision process, such as an early screening/orientation stage and a later evaluation/comparison stage as described by Russo and Leclerc (1994). Second, in another study, Glaholt and Reingold (2009b) manipulated exposure to decision alternatives by preexposing decision makers to a subset of the alternatives prior to a multialternative decision. Dwell sequence analysis showed that while the dwell duration bias was quite sensitive to prior exposure of decision alternatives, the dwell frequency bias was entirely insensitive to this manipulation. This provides further evidence that the dwell duration bias might reflect a process related to selective encoding of decision alternatives while the bias in dwell frequency might reflect an evaluation or comparison process that occurs after the alternatives have been initially encoded.

Additional evidence from eye movements for the presence of a screening process during multialternative visual decision tasks was reported by Glaholt, Wu, and Reingold (2009, 2010). For example, Glaholt, Wu, and Reingold (2010) manipulated decision task instructions such that participants chose between two sets of three items (set selection) or one out of six individual items (item selection), where the items were drawn from a set of images of everyday products (belts, sunglasses, shirts, or shoes). Of importance, the stimulus displays were identical between the two tasks, allowing for a direct examination of the impact of decision task instructions on patterns of eye movements. By comparing the first half and the second half of the decision period, it was shown that under the item selection instructions there was a significant reduction in the number of different items viewed from the first to the second half of the trial. Of interest, in contrast, there was no difference in the number of items viewed from the first to the second half of the trial under set selection instructions. This finding is consistent with the idea that in the item selection task, a screening process takes place whereby the number of items being actively considered is narrowed over the course of the decision.

In summary, the body of existing research employing eye movements for process tracing in decision research is relatively small. However, collectively this research has clearly demonstrated that eye movement measures provide an effective way to capture information search, and that eye movement measures are indeed sensitive to decision processes. Future research might seek to move beyond the more conventional use of eye movement monitoring in this domain, namely to observe decision makers’ pattern of information search, and to take advantage of the unique experimental manipulations that are possible with modern eye tracking technology. Specifically, eye tracking allows for powerful gaze-contingent manipulations that allow researchers to answer research questions that might otherwise be difficult or impossible to address. In the following section we present an experiment that illustrates some of these interesting possibilities.

**Experiment: Testing the Gaze Cascade Hypothesis**

In the present experiment we tested a specific hypothesis about the role of eye movements in preference decisions. By employing a gaze-contingent manipulation of exposure to decision alternatives, we were able to provide a direct test of the Gaze Cascade model proposed by Shimojo and colleagues (Shimojo et al., 2003; Simion & Shimojo, 2006, 2007). As a secondary goal, we further investigated the dissociation between the dwell frequency and dwell duration biases that was documented previously. In particular, Glaholt and Reingold (2009b) found that while the dwell duration bias was present throughout the decision time course, and was quite sensitive to whether or not decision alternatives had been exposed prior to the decision, the dwell frequency bias occurred later in the trial and was insensitive to the manipulation of stimulus exposure. Glaholt and Reingold (2009b) speculated that the two biases might map onto different stages of the decision process (following Russo & Leclerc, 1994), where the dwell duration bias might be related to a screening process that occurs during stimulus encoding, and the frequency bias might reflect an evaluative process that occurs later in the trial. The present manipulation provides convergent evidence for this dissociation in the context of the analysis techniques developed by Russo and Leclerc (1994). In addition, this experiment demonstrates the utility of eye tracking technology to provide experimental manip-
ulations (e.g., gaze-contingent display) that are impossible using other techniques.

To explain the gaze cascade effect (described in the previous section), Shimojo and colleagues (Shimojo et al., 2003; Simion & Shimojo, 2006, 2007) proposed the Gaze Cascade model. This model specifies two component processes related to looking behavior that interact during preference decisions. The first process is preferential looking, where one tends to look longer at the stimulus that one likes (Birch, Shimojo & Held, 1985). The second process is the mere exposure effect, where merely looking at a stimulus increases preference for that stimulus (Kunst-Wilson & Zajonc, 1980; Moreland & Zajonc, 1977, 1982; Zajonc, 1968). Shimojo et al. (2003) suggested that these two processes can combine to create a positive feedback loop (dubbed a Gaze Cascade) that progressively increases the activation of one of the decision options until it exceeds the threshold for response. This model represents a departure from previous decision making research, in that rather than assuming that eye movements reflect the sampling and processing of decision information (i.e., information search), the Gaze Cascade model holds that gaze itself plays an active role in the decision process. The model argues that for preference decisions, gaze both reflects the commitment to a decision alternative (e.g., the preference for that alternative), but also actively increases the commitment to that decision alternative (Shimojo et al., 2003).

Glaholt and Reingold (2009b) investigated predictions derived from the Gaze Cascade model. Specifically, the model makes the prediction that decision alternatives that are exposed for longer should be subject to a larger gaze cascade effect, and hence be more likely to be chosen, by way of the hypothesized positive feedback loop between mere exposure and preferential looking. However, the model argues for strong preference-specificity in this effect, and hence it should only hold for preference decisions and should be reduced or absent for non-preference decisions. In order to manipulate the degree of exposure to decision alternatives, Glaholt and Reingold (2009b) preexposed a subset of the decision alternatives prior to an 8-AFC decision (under preference or nonpreference instructions). Consistent with our prior findings (Glaholt & Reingold, 2009a), we observed a bias in dwell duration on the chosen item over the entire decision time course, and a bias in the frequency of dwells on the chosen item in the last few dwells in the trial. However, contrary to the prediction of the model, we found that the bias in dwell duration was actually larger for decision alternatives that were not preexposed than for those that were, and that the bias in dwell frequency was almost entirely insensitive to the exposure manipulation. We also found that pattern of gaze biases was extremely similar under preference and nonpreference decision instructions.

These findings are difficult to reconcile with the decision process specified by the Gaze Cascade model. However, there remains a specific set of conditions where increased stimulus exposure might affect gaze biases in the way predicted by the model. Our previous manipulation of stimulus exposure (Glaholt & Reingold, 2009b) involved a central presentation of the preexposed stimuli prior to the eight-alternative decision. The Gaze Cascade model describes a mechanism that is sensitive to differential stimulus exposure occurring during the ongoing decision. Consequently it remains possible that a manipulation of exposure to decision alternatives that occurs dynamically during the ongoing 8-AFC decision would produce results consistent with the gaze cascade hypothesis. In the experiment that follows we manipulated stimulus exposure in a way that addresses this potential concern. Using a gaze-contingent methodology, we controlled the maximum stimulus exposure duration within individual dwells during 8-AFC decisions. When participants directed their gaze to a stimulus alternative, the stimulus was removed from the display (blanked) after either a short duration (200 ms) or a long duration (400 ms). Stimuli that had been removed reappeared after the participant directed their gaze to another stimulus alternative. If the Gaze Cascade model is correct, stimuli with the longer exposure duration should exhibit stronger biases in looking behavior, and should be more likely to be chosen than stimuli with the short exposure duration. Critically, the model predicts that these exposure effects should be present in preference decisions and weak or absent in nonpreference decisions.
Method

Participants

All 16 participants were undergraduate students at the University of Toronto Mississauga, and each received $10 for their participation.

Apparatus

The eye tracker employed in this research was SR Research Ltd. EyeLink 1000 system. Following calibration, gaze-position error was less than 0.5°. Gaze position was sampled at 1000 Hz. Stimulus displays were presented on a 19-in. monitor. The participant’s monitor was set to a resolution of 1600 × 1200 and a refresh rate of 85 Hz. Participants were seated 65 cm from the display and used a chinrest with a head support.

Materials and Design

Stimuli consisted of a set of 400 grayscale images of photographic art (see Glaholt & Reingold, 2009a, 2009b). For each participant, half of the images were used in the Preference decision and half were used in the nonpreference control decision (Typicality decision). We found no correlation (across images) between the number of times an image was chosen in the Preference decision and the number of times it was chosen in the Typicality decision ($r = .01, n.s$), and hence the two decisions were likely to involve different decision criteria, possibly requiring participants to sample different information from the stimuli. The order of the decision tasks and the assignment of stimuli to each decision type were counterbalanced across participants. Within each decision task, the 200 photographs were randomly divided into 25 sets of 8, where each set corresponded to an 8-AFC trial. This process was then repeated yielding a total of 50 trials per decision type.

Procedure

In the Preference task, the participant was instructed to select, from the eight alternatives, the image that he or she liked the most. In the Typicality task (nonpreference control), the participant had to select the image that he or she judged to be most unusual (i.e., most out of the ordinary, least typical). Participants were informed that upon viewing an image, it would disappear after a short time and that it would reappear after they had moved on to another image, but that they should try to make the best decision they could.

At the beginning of each trial, the eight stimuli were presented in a 3 × 3 array, where each cell measured 8° × 8° of visual angle (400 × 400 pixels). The middle cell was empty except for a fixation circle. Direct foveal viewing time was limited using a gaze-contingent display: when the participant’s gaze entered a grid square containing a stimulus, that stimulus was removed from the display (blanked) after either a short duration (200 ms) or a long duration (400 ms) (Figure 2). In each trial, four of the eight alternatives were randomly assigned to the short exposure duration and the other four were assigned to the long exposure duration. The blanked stimulus reappeared 80 ms after the participant’s gaze had moved to another grid square. Participants were instructed that having reached a decision, they should look at the gray circle located in the center square and press a button on a video game controller. This caused the circle to turn green, which signaled the participant that the selection-by-looking tool was active, and that he or she should then fixate the chosen item in order to select it. Participants advanced to the next trial by fixating the central grid square and pressing a button on the video game controller.

Results and Discussion

Our analysis is divided into two sections. In the first section we tested predictions derived from the Gaze Cascade model. To reiterate, the Gaze Cascade model predicts that greater stimulus exposure should produce stronger biases in looking behavior in preference decisions, and these exposure effects should be weak or absent in nonpreference decisions. To quantify these effects, we employed analysis methods developed by Shimojo and colleagues (gaze likelihood analysis; Shimojo et al., 2003; Simion & Shimojo, 2006, 2007) as well as techniques we developed subsequently (dwell sequence analysis). In the second section, we investigated the apparent dissociation between the selectivity in the placement of dwells (e.g., the dwell frequency bias) and selectivity expressed in the
duration of dwells (e.g., the dwell duration bias). To accomplish this, we adapted the analysis technique introduced by Russo and Leclerc (1994) to separate the decision time course into stages based on the eye movement record. In particular, Russo and Leclerc argued that the onset of revisits to decision alternatives marked a transition to an evaluative stage of processing. Based on this model, we hypothesized that selectivity in the placement of dwells (i.e., the likelihood of viewing the chosen item) would increase greatly among revisit dwells compared with first encounters with a decision alternative.

**Testing the Gaze Cascade Model**

Prior to analyzing the eye movement data, we analyzed the probability that long exposure items were chosen over short exposure items and found that in the Preference task participants chose the long exposure items significantly more often than the short exposure items (chance = 0.50; M = 0.54, p < .05). However, in contrast to the preference-specificity predicted by the Gaze Cascade model, this effect was also present in the Typicality task (chance = 0.50; M = 0.55, p < .05). We speculate that participants may be slightly less likely to extract enough information from the short exposure items for them to be chosen, resulting in a slightly increased likelihood of choosing a long exposure item.

Following Shimojo et al. (2003) we produced gaze likelihood plots that display the proportion of time that gaze was directed at the chosen item over the 2-s period just prior to the response. The gaze likelihood plots are shown in Figure 3 (Preference in panel a, Typicality in panel b). A comparison of the plots by exposure duration and decision type indicated a very similar pattern across conditions and across decision types, with all plots showing an increasing tendency for the eyes to be directed toward the chosen item.

![Figure 2](image_url)

*Figure 2.* Schematic diagram of the gaze-contingent limited exposure manipulation employed for 8-alternative forced choice (8-AFC) decisions in this experiment. When the participant’s gaze entered a grid square containing a decision alternative, the alternative was blanked after a short exposure duration (200 ms) or a long exposure duration (400 ms), and it reappeared 80 ms after gaze was directed to another alternative.
item prior to the response. This runs contrary to the prediction of the Gaze Cascade model that the bias in gaze likelihood should be more pronounced for long exposure items, and specifically for preference decisions. There are, however, some slight differences in the gaze likelihood plots that are apparent. Over the last second prior to the response, in both tasks, the long exposure item appeared to reach a higher value earlier in the time course, than the short exposure item. On the other hand, the short exposure items reached a higher final gaze likelihood value than the long exposure items for both tasks. These differences in the gaze likelihood plots are difficult to interpret. In previous studies (Glaholt & Reingold, 2009a, 2009b), we found that the chosen item tended to be the last item fixated in a trial. Indeed, the value of the final point in the gaze likelihood curve is the probability of fixating the chosen item last. As a result, the shape of the final portion of the gaze likelihood curve was strongly influenced by the

Figure 3. Testing the Gaze Cascade model: (1) Gaze likelihood analysis, plotting the proportion of time that gaze was directed toward the chosen item, going back 2 s from the response, as a function of stimulus exposure duration (Preference in panel a, Typicality in panel b). We obtained 95% confidence intervals about each point in the time series using a bootstrapping procedure (Efron & Tibshirani, 1994); (2) Analysis of dwell frequency bias: proportion of dwells directed toward the chosen item, as a function of stimulus exposure duration, for each of 4 bins prior to the response, and for the first dwell bin (preference in panel c, Typicality in panel d); (3) Analysis of dwell duration bias: Mean dwell duration for the chosen and other items, as a function of stimulus exposure duration, for each of 4 dwell bins prior to the response, and for the first dwell bin (Preference in panel e, Typicality in panel f).
For each trial in each decision task, we identified a sequence of dwells, where a dwell was defined as the cumulative duration of all consecutive fixations from the moment the participant’s gaze enters a grid square containing an image, and until it exits that square. Preference and Typicality decisions were quite similar in terms of total number of dwells (Preference: $M = 19.4, SD = 7.8$; Typicality: $M = 23.2, SD = 7.7$), with the Typicality decisions having a slightly larger number of dwells, $t(15) = 2.57, p < .05$. As shown in Figure 3 (c, d, e, and f), we created 4 different dwell position bins going back from the response: the last two dwell positions (Last), positions 3–4 prior to the response ($−1$), positions 5–6 prior to response ($−2$), and positions 7–8 prior to response ($−3$).

In analyzing dwell duration, we conducted a $2 \times 2 \times 2 \times 4$ ANOVA that crossed Decision Type (Preference, Typicality), Choice (Chosen, Other), Exposure Duration (Long, Short), and Dwell Position Bin ($−3, −2, −1, Last$) as within-participant variables. The first dwell position bin was analyzed in a separate $2 \times 2$ ANOVA crossing Decision Type and Exposure Duration. In the first dwell position bin, no effects or interactions reached significance, and in all conditions the likelihood of dwells being directed to the chosen item in the first bin did not differ from chance (all $rs < 1.76$, all $ps > 0.1$). Consistent with the results of the gaze likelihood analysis, there was an increase in the bias in dwell frequency toward the chosen item in the last four dwell position bins, $F(3, 45) = 57.56, MSE = 0.012, p < .001$. However, unlike the prediction of the Gaze Cascade model the bias in dwell frequency was much lower for items with short exposure duration than for items with long exposure duration, $F(1, 15) = 6.55, MSE = 0.01, p < .05$, and the influence of exposure on the gaze bias in dwell frequency was not stronger in the Preference task than the Typicality task ($F < 1$). The only effect of decision type on dwell frequency was a trend toward a larger overall dwell frequency bias in the Typicality task, $F(1, 15) = 4.26, MSE = 0.01, p = .057$.
Consistent with the predictions of the Gaze Cascade model, the bias in dwell duration was significantly larger for long exposure items compared with short exposure items, $F(1, 15) = 10.76, MSE = 5.55 \times 10^{3}, p < .01$, and this interaction tended to be more pronounced in the later dwell position bins, $F(3, 45) = 2.80, MSE = 3.52 \times 10^{3}, p = .051$. However, we found no evidence in support of the critical prediction of the model that the effect of stimulus exposure duration on the gaze bias would be stronger in the Preference task than in the non-Preference control task (the three-way interaction between Exposure Duration, Choice, and Decision Type was not significant: $F(1, 15) = 1.34, MSE = 5.40 \times 10^{3}, p > .25$). The only evidence of task-specificity in the dwell duration bias appeared in a tendency for the bias to be larger overall in the Typicality task than in the Preference task, $F(1, 15) = 4.51, MSE = 3.98 \times 10^{3}, p = .051$.

Thus, together with our previous findings (Glaholt & Reingold, 2009b), we have failed to demonstrate the predicted effects of varying stimulus exposure regardless of whether increased exposure duration occurred as a result of prior exposure to decision alternatives, or through a relative increase during the ongoing decision. Furthermore, in the present study and in both of our previous investigations of the gaze bias phenomenon (Glaholt & Reingold, 2009a, 2009b) we have found no evidence of the preference-specificity that is central to the Gaze Cascade model. Accordingly, we would argue that these findings rule out the Gaze Cascade model as a viable account of the observed biases in looking behavior. Instead, such biases appear to be a more general characteristic of multialternative visual decision making.

**Gaze Bias in First Dwells and in Revisit Dwells**

A second goal of the present study was to further investigate the apparent dissociation between the bias in dwell frequency and the bias in the duration of dwells. In addition, we examined the possible link between these biases in looking behavior and the suggestion of multiple stages in multialternative decision making. Specifically, Russo and Leclerc (1994) suggested that during multialternative decisions, the point at which the decision maker begins to revisit decision alternatives marks a transition in the decision process from an early screening stage to a later evaluative stage where stimuli are compared directly (for a similar approach see Schoter, Berry, McKenzie, & Rayner, 2010). Accordingly, we contrasted two classes of dwells: *first dwells*, defined as dwells occurring in the period prior to the first refixation on a decision alternative in a trial, and *revisit dwells* which occurred later in the trial and were directed toward stimulus alternatives that were previously fixated during that trial (on average, participants viewed 5.12 different decision alternatives before revisiting any one of them). In an additional exploratory analysis, we examined the composition of dwells in terms of individual fixations by computing the mean number of fixations, and the mean fixation duration, for dwells on the chosen item and dwells on other items. Each measure was analyzed in a $2 \times 2 \times 2 \times 2$ within-subjects ANOVA that crossed Choice (Chosen, Other), Exposure Duration (200 ms, 400 ms), Encounter Type (First, Revisit), and Decision Type (Preference, Typicality). Given that there was a remarkably similar pattern of findings under the Preference and Typicality decision instructions, the results are described collapsing across Decision Type.

First we examined the bias in the placement of dwells (dwell frequency; Figure 4a). While there was a very small but significant increase in the probability of directing dwells to the chosen item compared with other items during first dwells, $F(1, 15) = 10.20, MSE = 0.001, p < .01$, this effect increased dramatically among revisit dwells, $F(1, 15) = 95.79, MSE = 0.002, p < .001$. The fact that the frequency of first dwells is roughly equivalent across chosen and other items might indicate that for the stimuli and decision tasks that we employed, parafoveal information is ineffective in guiding dwells toward promising decision alternatives early in the trial. To investigate this further, we computed the average serial position of the first dwell on the chosen item and the first dwell on other items and found that they did not differ significantly (chosen item: $5.01$, other items: $5.27$, $t(15) = 1.76, p = .1$).

Next we analyzed dwell duration. As can be seen in Figure 4b, dwells on the chosen item were longer in duration than dwells on other items (all $t$s > 2.27, all $p$s < 0.05), and this
The effect was larger for revisit dwells compared with first encounters, $F(1, 15) = 65.34$, $MSE = 893.56$, $p < .001$, and for long exposure stimuli than for short exposure stimuli, $F(1, 15) = 18.61$, $MSE = 967.06$, $p < .001$. More specifically, this pattern of effects is also present in mean fixation duration (Figure 4d) where the bias in mean fixation duration was larger for revisit dwells compared with first encounters, $F(1, 15) = 12.21$, $MSE = 249.83$, $p < .01$, and for long exposure stimuli compared with short exposure stimuli, $F(1, 15) = 5.96$, $MSE = 143.67$, $p < .05$. A similar pattern was present in the number of fixations per dwell (Figure 4c), where the bias was larger for revisit dwells than for first encounters, $F(1, 15) = 33.80$, $MSE = 0.01$, $p < .001$, and there was a trend toward a larger bias for long exposure stimuli compared with short exposure stimuli, $F(1, 15) = 3.40$, $MSE = 0.02$, $p < .1$. In summary, our results showed that the bias in dwell duration increases when more stimulus information is available within a dwell (i.e., long exposure vs. short exposure), and it also in-

Figure 4. Gaze bias in first dwells and revisit dwells: In each panel, measurements are displayed as a function of whether the dwell was directed to the chosen item or another item, whether the dwell was directed to a short (200 ms) or a long (400 ms) exposure stimulus, and whether the dwell was among first dwells (i.e., prior to the first revisit) or a revisit dwell. Error bars represent the standard error on the mean. (a) Proportion of dwells directed to the chosen item, and to other items. (b) Mean dwell duration. (c) Number of fixations per dwell. (d) Mean fixation duration.
creases when the dwell constitutes a return to a previously viewed stimulus (i.e., first dwells vs. revisit dwells). The lengthening of dwells reflects both a lengthening of individual fixations and an increase in the number of fixations per dwell.

The present findings and the findings from our previous experiments establish a pattern of an initial portion of the decision period where the dwell duration bias is present and the frequency bias is largely absent, and a later period that is marked by the emergence of the dwell frequency bias and an increase in the dwell duration bias. As suggested previously (Glaholt & Reingold, 2009b), this dissociation between the early and late portions of the decision period may map onto different stages of the decision process. In particular, it has been proposed (Beach, 1993; Russo & Leclerc, 1994; Senter & Wedell, 1999; Wedell & Senter, 1997) that in multialternative decisions participants employ an early “screening” process where the degree of encoding is not uniform across decision alternatives; rather, highly relevant alternatives are processed more deeply, and poor alternatives are processed to a lesser extent, or possibly even excluded from further processing. Consistent with this hypothesis, prior studies examining eye movements have found evidence of a narrowing in the set of decision alternatives considered over course of the decision period (Glaholt, Wu, & Reingold, 2009, 2010). In the present study we found additional evidence for the operation of such a screening process. Specifically, we found that the dwell duration bias is sensitive to the amount of stimulus information that is available within a dwell (i.e., long vs. short exposure duration). When more stimulus information is available, we observed a greater differentiation in dwell duration between the chosen and not chosen items. This might reflect an early stage of processing where decision alternatives are initially encoded, and relevant alternatives (e.g., the chosen item) are encoded to a greater extent than poor alternatives. The later stage of the decision period might involve deeper evaluation of relevant alternatives, and direct comparisons between alternatives, reflected in an increased dwell duration bias and an increase in the frequency of dwells on the chosen item.

**General Discussion**

In this article, we reviewed the status of eye movement recordings as a process tracing methodology in decision making research. Since the late 1970s, eye tracking technology has become an increasingly valuable method of monitoring decision makers’ information search behavior. Early research demonstrated that eye movement monitoring can provide a variety of process tracing measures that corroborate those obtained from the more traditional methods such as information search displays and verbal protocols. More recently, advances in eye tracking technology have afforded several unique advantages for this methodology. In particular, modern eye tracking technology allows for extremely precise measurement of the spatial and temporal profile of decision makers’ information sampling. Of importance, in comparison to other methods, eye movement monitoring imposes very few external demands on the decision maker, and as such is likely to portray decision processes as they occur naturally. Beyond providing precise monitoring of information search, eye movement recordings can be used to manipulate the information presented to the decision maker in gaze-contingent fashion. By updating the display based on the viewer’s gaze position, a variety of unique experimental manipulations are possible, such as precise control over exposure to individual stimuli. As illustrated in the present experiment, this sort of manipulation can allow researchers to test specific hypotheses about decision processes that might otherwise be difficult or impossible to address.

One potential problem with eye movement monitoring as a process tracing method is that when decision makers’ are allowed to freely view a display, they may be able to process information outside of the focus of their gaze, which might undercut the ability of eye movement monitoring to capture the true pattern of information search. However, as has been argued elsewhere, the focus of gaze and the focus of attention tend to be tightly coupled during natural viewing. But moreover, eye tracking can be applied to tackle this issue directly. For example, evidence of the processing of peripheral information can be derived from the pattern of information sampling. In the present experiment, we found that the bias in the placement of
dwell sequence, which revealed dissociable biases in dwell frequency and dwell duration over the decision time course.

Rather than reflecting a Gaze Cascade mechanism, we interpreted these two biases in the context of prior process tracing research. Specifically, the bias in dwell duration and the bias in dwell frequency might reflect different stages of the decision process. It has been suggested that in multialternative decisions, because of limits in information processing capacity it may be inconvenient or impossible for decision makers to completely encode (i.e., process holistically) all of the alternatives and compare them simultaneously (Ford et al., 1989; Payne, 1976; Payne et al., 1993). Consequently, decision makers may engage in a “screening” stage characterized by selective processing, where relevant alternatives are processed in greater depth, and poor alternatives may be subject to shallow encoding or excluded from further processing altogether (Beach, 1993; Russo & Leclerc, 1994; Senter & Wedell, 1999; Wedell & Senter, 1997). A key characteristic of such a screening process is that stimuli are encoded to a different degree depending on their relevance to the decision task. The bias in dwell duration is consistent with differential encoding according to task relevance, and hence it might reflect the operation of such a screening process during multialternative decisions. In contrast, the bias in dwell frequency might reflect a later evaluative stage of processing that involves the direct comparison of alternatives and results in a higher frequency of dwells on the chosen item. Consistent with this possibility, in the present experiment and in prior work (Glaholt & Reingold, 2009b), we found the dwell duration bias to be quite sensitive to manipulations of stimulus exposure duration while the bias in dwell frequency was not. Together these findings suggest that the dwell duration bias is somehow related to the encoding of decision alternatives. In contrast, the dwell frequency bias is likely to be less related to the encoding of alternatives, and perhaps instead reflects another process (possibly postencoding) such as the evaluation and comparison of relevant alternatives. However, further research is clearly required to test these ideas.

At present, it is apparent that eye movement recordings might be best employed in a combined approach with other process tracing methods. As has been argued by Riedl et al. (2008) with regards to information search display paradigms, convergent evidence from multiple techniques (including verbal reports, analysis of outcomes, etc.) may be required to specifically identify the nature of the cognitive processes that occur during decision making. In this regard, there is a possible avenue of future research that has yet to be explored, but that has the potential to provide additional information about decision processes. Recently, there has been an explosion of research in the area of decision neuroscience (cf., O’Doherty & Bossaerts, 2008; Sanfey, 2007; for reviews see Rangel, Camerer, & Montague, 2008; and Glímer, 2003). In line with the process tracing approach, decision neuroscience seeks to detect cognitive processes that occur over the
decision time course prior to the final behavioral response. Modern eye tracking technology is now available to sample gaze position at a rate that matches or exceeds the rate of sampling of brain activity available with current neuroimaging methods. In particular, eye movement monitoring may be especially useful in providing temporal markers of decision processes for which neural activity can then be observed in the neuroimaging record. This combined method has recently been successfully employed in the study of visual cognition, and holds considerable promise as a future process tracing method in decision research.

In summary, our review indicates that eye movement monitoring is poised to be an increasingly valuable process tracing technique in the next wave of decision making research. Recent advances in eye tracking technology have brought about a dramatic improvement in the quality of eye movement data and in the ecological validity of this methodology. Eye movement monitoring now affords a variety of experimental manipulations, and in particular, rigorous experimental control can be achieved by the use of gaze-contingent techniques. Finally, the combination of eye movements and other process tracing techniques have strong potential for future research.

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