Looking at Nothing Indicates Memory Search in Multiattribute Decision Making

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Abstract

The common methods for studying heuristics in memory-based multiattribute decisions provide outcome and response time data but leave the foregoing cognitive processes in the dark. We demonstrate a novel process-tracing method that uses the looking-at-nothing phenomenon to study memory search and cue processing via eye tracking. Participants learned cue information of decision alternatives in spatial frames and later were presented with emptied displays of two alternatives in binary choice trials. With freely chosen and with instructed decision strategies, fixation patterns on former cue locations were in line with memory search and cue processing as postulated for lexicographic and compensatory strategies.

Keywords: Multiattribute decision making, Probabilistic inference, Eye tracking, Take-the-best heuristic, Spatial index

Introduction

Integrating multiple cues in decision making in a completely rational manner that factors in all available information is widely assumed to be cognitively too demanding. Therefore, simple but efficient heuristics are suggested that are applicable in specific task domains (e.g., Gigerenzer & Todd, 1999). The domain we will deal with here consists of simple probabilistic inference tasks with two alternatives and binary cues (e.g. “Which of the cities A and B has more inhabitants?”). Perhaps the best known heuristic for this kind of tasks is Take-the-Best (Gigerenzer & Goldstein, 1996), which belongs to the class of lexicographic strategies (LEX). In a first step, a person using this strategy selects the (subjectively) most valid cue and looks up the cue values of both alternatives. If one alternative has a positive cue value (indicating a higher value on the target dimension) and the other has not, information search is stopped, and the alternative with the positive value is chosen. If the first cue does not discriminate between the alternatives, the second most valid cue is accessed, and so forth.

LEX is a non-compensatory strategy, because cues lower in validity are disregarded. Thus, cues with a low validity cannot compensate for a difference on a more valid cue dimension. An example of a simple but compensatory heuristic is the equal weight strategy (EQW), which ignores cue validities. With this strategy, the positive cue values are counted for each alternative and the alternative with the higher number of positive cue values is chosen.

The third strategy we will consider here - the weighted additive rule (WADD) - is also compensatory but uses information about cue values and validities fully. Cue values are weighed by cue validities and summed up. It has often been claimed that this strategy is computationally too demanding to be performed in a sequence of serial and deliberate cognitive processes. However, WADD can be conceived as a paramorphic model because the choices expected from WADD could be brought about by intuitive-automatic processes as well. Automatic processes that approximate WADD predictions have been simulated as parallel constraint satisfaction (see Glöckner & Betsch, 2008).

Methodologically, it poses a challenge to infer which strategy an individual used in a probabilistic inference task. One reason is that in tasks with a small number of alternatives, several strategies predict the same choices. More importantly, simple strategies are complete sub-models of more complex ones. With appropriately chosen weights, WADD could produce decisions that are indistinguishable of the predictions of LEX or EQW (Martignon & Hoffrage, 2002). Hence, an individual’s choices may appear to be generated by LEX even if she is using cognitive processes that are not assumed in this heuristic.

Therefore, process-tracing methods are often used in addition to outcome-based measures. The most prominent process-tracing method is the computer-based information board called Mouselab (Payne, Bettman, & Johnson, 1993). Mouselab records which pieces of information a participant seeks, in which sequence the information is accessed, and how much information is gathered. A central idea is that different decision strategies should be accompanied by different information search patterns. For non-compensatory strategies like LEX a cue-wise information search is expected. A LEX-user that has looked up a cue value of one alternative should subsequently check the value of the other alternative on the same cue dimension and then either decide or, if the values do not differ, switch to the next cue dimension. In contrast, compensatory strategies should be associated with an alternative-wise information search. Users of these strategies should search for all cue values of one alternative before they turn to the other alternative.

Process-tracing methods like Mouselab necessitate that all relevant information is provided by the experimenter and accessible for the participant on the computer screen (or on written information cards). However, in many real-life situations decisions have to be made from information that is stored in long-term memory. Additionally, proponents of simple heuristics argue that particularly memory-based decisions induce selective and heuristic processing to limit the costs of memory retrieval (Gigerenzer & Todd, 1999). Hence, "inferences from memory" and not "inferences from givens" should be studied to test these postulates. Thus, there is a need for process-tracing methods that can be applied in studies investigating memory-based decisions.

We propose a method that sticks closely to the basic idea of Mouselab. It draws on results by Richardson and Spivey (2000) demonstrating a close link between eye movements and memory retrieval. In a series of experiments, these authors found that participants recalling visually presented information saccade more often to the (empty) region of space where the information was originally presented than to any other region (for an overview of studies on this "looking at nothing" phenomenon, see Ferreira, Apel, & Henderson, 2008). Thus, if specific cue dimensions are associated with specific locations it might be possible to reveal which cue information a person searches in memory by tracking her eye movements.

In the experiment reported below, our participants worked through a learning phase, in which each cue dimension was presented in a different fixed location of a spatial frame. In the decision phase, we presented two empty spatial frames next to each other and recorded participants' eye movements on these empty frames while they recalled cue information to decide between the two alternatives. Our objective was to test whether participants who were classified as LEX-users based on their decision outcomes showed different gaze patterns than participants classified as using compensatory strategies. More specifically, we report tests of the following three hypotheses:

1. As soon as a cue value on one alternative is found, LEX-users should look for the respective cue value of the other alternative. In contrast, users of compensatory strategies should search for complete cue information on one alternative first. Hence, LEX-users should switch their gaze more often between alternatives than users of compensatory strategies, that is, there should be more transitions between alternatives per second of a trial for LEX-users than for users of compensatory strategies.

2. Because memory-retrieval of LEX-users is more extensive when differentiating cues have lower relative validity, the absolute frequency of transitions between alternatives should increase linearly with the validity rank of the first differentiating cue. In contrast, for users of compensatory strategies the validity rank of the first discriminating cue should not affect the frequency of transitions.

3. LEX-users should disregard cues lower in validity as soon as a higher cue differentiates between alternatives. Hence, fixation durations on former locations of cue values lower in validity should be shorter in trials, in which a cue higher in validity differentiates. Again, users of compensatory strategies should not be affected by the validity rank of the first discriminating cue and the former locations of all cue values should be fixated for about the same amount of time.

Experiment

The experiment consisted of a learning phase, in which the participants acquired cue knowledge about six objects, followed by two decision phases. In the first decision phase, pairs of objects were presented to the participants for binary choice. In this phase, participants were not instructed with regard to the strategy they should use. Thus, the first decision phase followed a quasi-experimental logic. Here, the aim was to identify groups of participants who spontaneously employed different strategies and to test whether these groups show different patterns of gaze behavior as predicted in our hypotheses. We added a second decision phase to gain better control over the strategies participants used. In this phase, we presented the same binary choice items as in the first phase, but we directly instructed the participants to employ a certain strategy. Thus, with the second phase we realized a simple one-factorial design with two experimental groups (LEX-, EQW-instructions).

Method

Participants. Fifty-three students at the University of Greifswald participated in the experiment (43 women, 10 men; mean age 21.9 years). They received partial course credit for their participation. They were assigned randomly to the different strategy conditions in the second decision phase.

Materials. The participants learned cue descriptions of six alternatives. These alternatives were mushrooms characterized by the four cue dimensions consistency, cell wall material, mineral, and spread. Each of the cue dimensions could have three different values (consistency: soft, elastic or firm; cell wall material: protein, cellulose or lipid; mineral: magnesium, zinc or potassium; spread: frequent, medium or rare). The critical cue values (elastic, protein, magnesium and rare), which indicated a higher value on the target dimension (toxicity of the mushrooms), were not revealed to the participants until the learning phase was completed. In the decision phase, we presented pairs of the mushrooms for binary choice.

A complete paired comparison of the six cue patterns yields 15 choice tasks. The six cue patterns were constructed in a way that allowed for an individual strategy classification of the participants based on the vector of their choices in these 15 tasks (see Bröder & Schiffer, 2003a). Among the 15 binary choice tasks was a sufficient number of items for which each of the decision strategies considered here yields a distinct prediction. (A more detailed description of the cue patterns is given in Renkewitz & Jahn (2010), where we report an earlier experiment in which we used the same patterns.) To attain a more reliable strategy classification, all 15 items were presented twice in both decision phases. For the second presentation of each item, the order of the alternatives was reversed. Thus, each decision phase consisted of 30 binary choice items after two practice trials.

Figure 1 exemplarily shows two alternatives and their cue descriptions as they were presented in the learning phase. Each mushroom was symbolized by a different geometrical figure. Written descriptions of the cue values appeared in four rectangular frames that were arranged along the borders of the geometrical figures. The position of the frames was constant across all alternatives. For a given participant, values on the same cue dimension were always shown in the same frame (e.g., the respective value of the cue "consistency" was presented in the lower left frame for all mushrooms learned by this participant). Thus, each cue dimension was tied to specific spatial coordinates. We counterbalanced the position of the cues across different validity ranks. For half of the participants, the cues were arranged clockwise in descending order of validity starting from the upper left frame. Hence the two most valid cues appeared in the two upper positions. For the remaining half of participants, the cues were arranged counter-clockwise starting from the lower left frame. Here, the two most valid cues appeared in the two lower positions. Additionally, the labels of the cues were counterbalanced across validity ranks. We used the two validity orders "consistency, cell wall material, mineral, spread" and "spread, mineral, cell wall material, consistency".

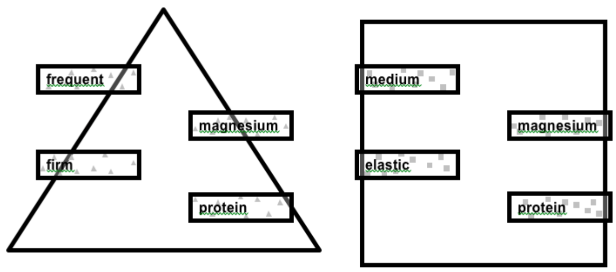

Figure 1: Two of the six alternatives as they were presented in the learning phase. In the decision phases, the rectangular frames containing the four cue values were empty.

In each trial of the decision phases, two of the geometrical figures were presented side by side. The size of the figures was the same as in the learning phase. The rectangular frames that contained the cue values in the learning phase were now empty. So, participants had to actively search their memory for cue information to be able to decide which of the two mushrooms was likely to be the more toxic one.

Procedure. At the beginning of the learning phase, the six alternatives and their cue values were presented one by one. Afterwards, the participants had to reproduce the cue values repeatedly in several testing cycles. The learning phase continued until the participants correctly reproduced at least 22 of the 24 cue values in a final memory test (see Renkewitz & Jahn, 2010, for more details on the learning phase).

Before the decision phases, the participants were informed about the validity ranks of the cues and the critical cue values. For instance, when the corresponding order of cue validities was used, participants were told that spread gave the most important hint to toxicity and that only rare mushrooms were likely to be toxic. The second most important hint was the mineral and only mushrooms predominantly containing the mineral magnesium were likely to be toxic, and so on. Additionally, a list showing the attributes of the 'typical toxic mushroom' was shown.

The 30 test trials of a decision phase were organized in two blocks. Each block consisted of the 15 binary choice items resulting from a complete paired comparison of the six mushrooms. Within each block, choice items were presented in random order. Participants responded with two keys on a standard keyboard.

After the first decision phase was finished, participants were given the strategy instructions for the second decision phase. In the LEX-condition, participants were told to consider attributes in descending order of importance and to decide according to the first attribute indicating that one of the two mushrooms was more toxic. All attributes of lower importance should be ignored. In the EQW-condition, participants were instructed to decide on the basis of the number of attributes indicating that a mushroom was toxic. If both mushrooms had the same number of 'toxicity attributes' they should guess. Subsequent to these explanations, an example of the application of the respective decision rule was given. In this example two cue patterns were used that were not part of the test set.

During both decision phases, eye movements were recorded with a desk-mounted SMI RED eye tracker sampling pupil position at 60 Hz.

Results

Behavioral data. We classified the decision patterns of the participants as most probably generated by LEX, EQW, WADD or a guessing strategy with the maximum-likelihood strategy classification method (Bröder & Schiffer, 2003a, 2003b). The strategy percentages in both decision phases are shown in Table 1. In the first phase, when there were no strategy instructions, 49% of the participants were classified as using the LEX-heuristic. This frequency of LEX-users corresponds closely to the findings of similar studies on memory based decision making using verbal stimulus material (Bröder & Schiffer, 2003b; Bröder & Schiffer, 2006; Bröder & Gaissmeier, 2007; Jahn, Renkewitz & Kunze, 2007). The classification results in the second decision phase suggest that the strategy instructions were largely successful. Thus, 80% of the participants instructed to employ the LEX-heuristic appeared to use this strategy and 89% of the participants instructed to use EQW were classified as using one of the compensatory strategies (EQW or WADD).

Table 1: Frequencies (and percentages) of strategy classifications in decision phase 1 (free strategy selection) and decision phase 2 (with LEX or EQW instructions)

Condition	Strategy classification					N
	LEX	EQW	WADD	Guessing	unclassified	N
Decision phase 1						
Free	26 (49.1)	14 (26.4)	9 (17.0)	1 (1.9)	3 (5.7)	53
Decision phase 2						
LEX	20 (80.0)	1 (4.0)	1 (4.0)	2 (8.0)	1 (4.0)	25
EQW	2 (7.1)	18 (64.3)	7 (25.0)	1 (3.6)	0 (0.0)	28

Table 2: Mean absolute number of transitions between alternatives depending on the position of the first differentiating cue for groups of participants with different strategy classifications in both decision phases

Strategy	Validity rank of first discriminating cue: 1		2		3		4	
	M	95% CI	M	95% CI	M	95% CI	M	95% CI
Decision Phase 1 (free)								
LEX	4.64	3.57-5.71	7.00	5.72-8.28	10.45	7.07-12.93	8.07	6.52-9.61
COMP	6.11	4.93-7.29	6.58	5.17-7.99	5.79	3.05-8.52	5.70	4.01-7.40
Decision Phase 2 (instructed)								
LEX	3.37	2.18-4.55	5.80	4.31-7.28	7.35	5.94-8.76	9.32	7.39-11.25
COMP	5.62	4.58-6.65	5.30	3.99-6.60	4.67	3.38-5.85	5.10	3.41-6.79

Analyses of eye gaze data. In the analyses of gaze behavior we did not consider participants who remained unclassified or were classified as using a guessing strategy because we held no hypotheses concerning these participants. In the first decision phase, we excluded one additional participant (classified as EQW-user) from further analyses because of her unusually long decision times. In the second decision phase, we restricted the analyses to those participants that appeared to follow the instruction to employ the LEX-heuristic and those participants who were classified as using one of the compensatory strategies under EQW-instructions. Finally, we discarded all trials (3.0% in the first phase and 4.4% in the second phase) from the analyses of gaze behavior, in which the tracking data for more than 40% of the trial duration were missing (due to blinks, looking off the screen, or lost pupil or corneal reflectance).

In all of the following analyses, we merged the eye tracking data of EQW- and WADD-users as the result pattern for both compensatory strategies was generally the same and no statistically significant differences occurred between these two groups.

Transitions between alternatives per second. To determine the number of transitions between alternatives, we defined two areas of interest (AOIs), each of which covered one alternative and, thus, almost one half of the screen. A transition was defined as two successive fixations in different AOIs. We counted the number of transitions per trial and divided this number by the trial duration (in seconds) to obtain an index of gaze transitions. The means of this index corroborate our first hypothesis: With instructed decision strategies, LEX-users (M = 0.68) switched their gaze faster between alternatives than users of a compensatory strategy (M = 0.46), 95% CIs [0.58, 0.78], and [0.41, 0.51], respectively, $t(43) = 3.52$, $p = .001$, d = 1.08. In the first decision phase, when participants spontaneously adopted a decision strategy, the same difference between the LEX-heuristic (M = 0.60) and compensatory strategies (M = 0.39) was found, 95% CIs [0.54, 0.66], and [0.34, 0.44], respectively, $t(46) = 4.90$, $p < .001$, $d = 1.45$.

Transitions between alternatives depending on the validity rank of the first discriminating cue. According to our second hypothesis, for LEX-users the absolute number of transitions between alternatives should depend on the validity rank of the first discriminating cue in a decision item. The lower the validity of the first discriminating cue the more transitions should occur. In contrast, the gaze behavior of users of a compensatory strategy should be unaffected by the validity rank of the first discriminating cue.

To test this hypothesis, we split the 30 decision items into four sets, according to the rank of the best discriminating cue. Table 2 depicts the mean number of transitions in each of the four sets for LEX-users and for users of a compensatory strategy in both decision phases. Under instructed strategy conditions, for LEX-users the mean number of transitions increased monotonically with the validity rank of the first discriminating cue, as expected. For users of compensatory strategies no systematic effect was associated with the validity of the best differentiating cue. This interaction effect of strategy classification and validity rank of the first discriminating cue was confirmed in a two-way mixed ANOVA, Greenhouse-Geisser corrected $F(2.28, 98.13) = 22.71$, $p < .001$, $\eta_p^2 = .35$. When participants chose freely between decision strategies, we found a similar result pattern. For LEX users the number of transitions again increased markedly (but not monotonically) with the validity rank of the first discriminating cue. For users of a compensatory strategy this factor had no impact. The corresponding interaction effect was again statistically significant, Greenhouse-Geisser corrected $F(1.79, 82.25) = 8.42$, $p = .001$, $\eta_p^2 = .16$.

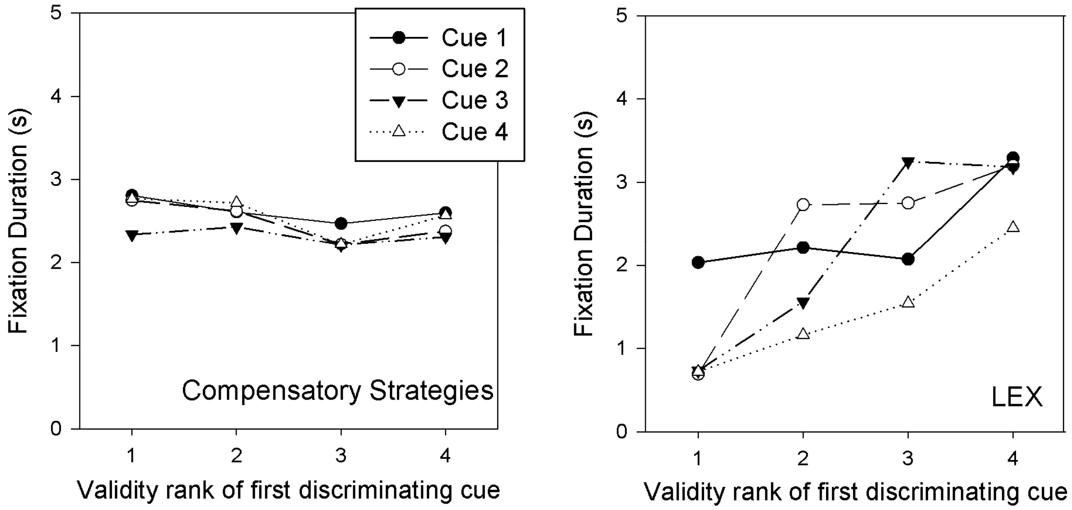

Figure 2: Mean fixation durations at cues with different validities depending on the validity rank of the first discriminating cue in decision phase 2 (instructed strategies). Data are presented separately by strategy classification.

Fixation durations at former locations of cue values. To assess fixation durations at former locations of cue values, we defined AOIs around the empty rectangular frames that had contained the cue values in the learning phase. These AOIs exceeded the original frames by 30 pixels in each direction.

For each trial and each cue, we determined the summed duration of all fixations in the two AOIs pertaining to the respective cue (one AOI for each alternative). These summed durations were averaged per participant across all trials, in which the first discriminating cue had the same validity rank. For participants of all strategy classifications, fixation durations exhibited a gaze bias towards the cue locations in the upper half of the stimuli. This bias was independent of both the specific cues presented at these locations and the validity rank of these cues. Hence, as we were interested in the average fixation durations at locations of cues with different validity ranks, we calculated weighted means across the groups of participants for which the two most valid cues appeared in the upper part of the stimuli and the groups for which these cues appeared in the lower part.

In Figure 2, the weighted mean fixation durations at cues with different validities are plotted against the validity rank of the first discriminating cue for the second decision phase with instructed strategies. As can be easily seen, we found clearly different result patterns for LEX-users and users of compensatory strategies.

Under instructed strategy conditions, users of compensatory strategies looked approximately equally long at all four cues and their fixation durations were unaffected by the validity rank of the first discriminating cue in a decision item. Consequently, in a three-way mixed ANOVA the effects of Cue, Greenhouse-Geisser corrected $F(2.21, 50.88) = 0.22$, $p = .83$, $\eta_p^2 = .01$, First Discriminating Cue, $F(2.33, 53.67) = 2.06$, $p = .13$, $\eta_p^2 = .08$, and their interaction, $F(5.00, 114.96) = 0{,}45$, $p = .81$, $\eta_p^2 = .02$, were all not significant (the third factor Position of the Two Most Valid Cues with the levels Upper Half or Lower Half was introduced to control for the gaze bias towards the upper half of the stimuli).

In contrast, in items in which the most valid cue discriminated, instructed LEX-users fixated this cue considerably longer than all other cues. When the second most valid cue was the first to discriminate, the largest increase in fixation durations occurred for this cue. However, also the third cue and the fourth cue were fixated longer than in items in which the first cue discriminated. Similar changes in fixation durations emerged when cues with a lower validity were the first discriminating ones. Thus, the data reveal two trends: First, as expected, cues with a low validity are fixated longer, when no cue higher in validity discriminates. Second, there is a tendency towards all cues being fixated longer when the validity rank of the first discriminating cue is low. Correspondingly, the interaction effect of Cue x First Discriminating Cue, $F(4.18, 75.31) = 5.75$, $p < .001$, $\eta_p^2 = .24$, and the main effect of First Discriminating Cue, $F(1.77, 31.83) = 16.94$, $p < .001$, $\eta_p^2 = .49$ were significant. The main effect of Cue was not statistically reliable, $F(1.55, 27.94) = 2.57$, $p = .11$, $\eta_p^2 = .13$.

When the participants spontaneously adopted a decision strategy in the first decision phase, the pattern of results was similar but somewhat noisier. For users of compensatory strategies, there were again no statistically significant effects. For LEX-users, the effect of First Discriminating Cue was confirmed, $F(2.08, 49.85) = 6.51$, $p = .003$, $\eta_p^2 = .21$, whereas the interaction effect of Cue x First Discriminating Cue was no longer statistically significant, $F(4.83, 115.96) = 1.94$, $p = .09$, $\eta_p^2 = .08$.

Discussion

The observed fixation patterns on emptied displays of decision alternatives differed markedly and in line with predictions depending on the decision strategies employed. If according to a lexicographic strategy more comparisons between single cue values of alternatives were necessary, more transitions between alternatives were recorded. Furthermore, even the fixation durations on the former locations of specific cues reflected the cues' relative importance according to a lexicographic or a compensatory strategy.

Thus, tracking fixations on emptied information displays provided indicators of information search in memory-based multiattribute decisions similar to those provided by Mouselab methods for "inferences from givens" (Payne, Bettman, & Johnson, 1993). This proves a novel process-tracing method applicable to memory-based decisions. The present results corroborate the outcome-based strategy classification method (Bröder & Schiffer, 2003a) and add to previous response time data on strategies in memory-based multiattribute decisions (Bröder & Gaissmaier, 2007). Now, there is a way to analyze overt behavior that seems to indicate which cognitive processes determine response times and decision outcomes.

The looking-at-nothing phenomenon has been interpreted as an attempt at memory retrieval that triggers an involuntary gaze shift to the former location of the sought information (Richardson & Spivey, 2000). The former location is specified by a spatial index in an integrated representation encompassing conceptual, linguistic, visual and spatial information (Ferreira, Apel, & Henderson, 2008). In the present experiment, several instances of memory retrieval were required in a single binary choice trial. The more information had to be retrieved according to a strategy, the more fixations occurred, however, locations were frequently refixated. Based on the current data we cannot decide whether these refixations are due to repeated retrieval attempts or further processing of the already retrieved information in working memory. We presume that they indicate processing of retrieved information similar to eye movements that occur while visuo-spatial imagery is experienced during discourse processing (Johansson, Holsanova, & Holmqvist, 2006). If this proves correct, the exposition of the LEX strategy has to be modified. The prolonged response times predicted and observed for LEX-users if cues lower in validity have to be processed seem to be due not only to additional memory retrieval, but to extended pondering that includes cue information that does not affect the final decision.

In our attempt to exploit the looking-at-nothing phenomenon for process tracing, we have shown that it manifests itself rather robustly. Here, encoding and retrieval were separated by multiple encoding and retrieval instances with respect to overlapping physical locations. Furthermore, spatial indexing operated relative to visual context that varied in its physical location. Hence, we think that looking-at-nothing has wide applicability. Observing information search on emptied displays opens up a window on the cognitive processing of memorized information.

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