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Authors
Creel, Emily

Moss, Jarrod

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Exploring the Predictive Power of Eye Movements on Insight Problem Solving

Emily Williamson Creel (eaw361@msstate.edu)
Jarrod Moss (jarrod.moss@msstate.edu)

Department of Psychology, Mississippi State University
Mississippi State, MS 39762 USA

Abstract

The precise mechanisms precipitating the process of representational change in problem solving have been investigated for nearly a century. One current hypothesis is that analyzing the unchanging elements of previous attempts may facilitate restructuring. We investigated this hypothesis by providing solvers with three common examples of unsuccessful problem attempts, their own problem attempts, or no previous attempts. The prior attempts conditions eliminated the need to rely on working memory to access previous unsuccessful attempts. While there was no evidence for an overall effect of the prior attempts conditions, cognitive reflection was identified as a reliable predictor of restructuring and solving. Eye-tracking data were collected to further investigate the contributions of these systems to fixations while solving. The current study is an exploratory analysis of this data, with analyses focusing on participants' fixations on problem-irrelevant space and unsuccessful attempts.

Keywords: problem-solving; eye-tracking; insight; representational change

Mental representations have been investigated in problem-solving research over many decades by attempting to operationalize insightful solutions. The current study operates under the perspective that insight is the realization of a solution due to sudden changes in the mental representation of the problem rather than existing as its own category of problems. This insightful process is typically characterized by an initial flawed representation of the problem, followed by a period of difficulty generating possible solutions that is referred to as "impasse," that can be overcome through a change in the way the problem is being mentally represented (Maier, 1931). The type of change required to overcome impasse differs by the context of the problem and is referred to as "restructuring."

Unsuccessful solving is attributed to an inability to move past the impasse phase or failing to inhibit irrelevant information, often because people become fixated on their initial faulty representation of the problem. This initial representation consists of an individual's understanding of the provided problem information as well as any related prior experience that could be associated with problem elements, understanding of the goal state, understanding of the operators that can be acted on to reach the goal state, and understanding of the elements that can or cannot be acted on to reach the goal state (Newell & Simon, 1972; Ash et al., 2006). Existing theories primarily address the development of the initial problem representation as well as the initial search period, though a detailed understanding of the cognitive processes driving the internal movement from a period of impasse to restructuring remains elusive.

Gestalt psychologists would observe (for a review see Kohler, 2015) their participants suddenly realizing the solutions to difficult problems. These researchers attributed this sudden solving to an unconscious reorganization of the problem elements, but they could not yet explain the reasoning behind why some of these problems were more difficult to overcome than others. Their idea of restructuring being a key factor to successfully solving these intentionally misleading problems remains in current theories, including Representational Change Theory (Knoblich, Ohlsson, Haider, & Rhenius, 1999). This theory attributes both restructuring and differences in problem difficulty as a function of activation spread to associative elements beyond the initial flawed representation. In this theory, restructuring occurs when people waive various constraints they were placing on the problems themselves or when they realize problem components can be decomposed and individual elements operated on.

Previous Attempts and Insight

While Representational Change Theory captures some of the modern interpretations regarding how impasse is overcome through restructuring, it still fails to explain the cognitive processes that direct this internal movement from impasse to a successful representation. What internal changes allow activation to spread in a manner that leads to successful restructuring? If activation is spread to relevant information, what cognitive processes determine whether that information will be successfully incorporated into the updated representation?

A recent experiment analyzing conceptual recoding using variations of the Nine Dot Problem proposed that experimentally analyzing the information learned from unsuccessful problem attempts may help answer some of these questions (Ormerod et al., 2022). This strategy of gleaning useful information from prior attempts has been previously identified through observing participants re-attempt strategies they had already tried (Maier, 1931) and having solvers talk aloud while solving. One of these talk-aloud studies was performed by Kaplan and Simon (1990) using the mutilated checkerboard problem, and they termed the "Notice Invariants Heuristic" an inferred strategy in which participants identified unchanging elements between their attempts.

Reanalyzing prior strategies may facilitate restructuring by allowing participants to reflect on the unchanging elements

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and personal constraints they are placing on the problem. This reordering of problem elements may then allow activation to spread to any prior knowledge that could be relevant to the problem solution. These possible relationships will be explored within this experiment by having participants solve three insight problems with varying levels of access to unsuccessful problem attempts, exploring the interactions between problem solving behaviors and individual differences hypothesized to affect these behaviors, and using eye-tracking to determine if solving behaviors differ by whether solvers have access to prior attempts.

Providing previous unsuccessful problem attempts is intended to offer a dynamic way for solvers to explore the problem and discover which manipulations may lead to progress towards the solution. Within Representational Change Theory, this could be viewed as an example of identifying and relaxing unnecessary constraints placed on the problem representation due to relevant prior experience with any of the problem elements. The Notice Invariants Heuristic suggests that people can then focus their efforts on what could be manipulated within their representation. While, to our knowledge, no one has directly examined the role that analyzing previous problem attempts has on the likelihood of restructuring, several authors have mentioned the possibility of this heuristic being used by solvers (Ash & Wiley, 2006; Kaplan & Simon, 1990; Ormerod et al., 2022).

Eye Tracking and Insight

Authors of the Representational Change Theory later bolstered their ideas using eye-tracking methods on participants solving matchstick problems, which have been used to explore insight in a variety of different studies (Knoblich, Ohlsson, Haider, & Rhenius, 1999; Knoblich et al., 2001; Strickland et al., 2022). They consist of false addition and subtraction problems where the values are roman numerals and all problem elements are constructed with matchsticks (e.g., IV = III + III), with the goal for participants to move one matchstick to make the problem statement true (e.g., VI = III + III). Knoblich, Ohlsson, and Raney (2001) found that participants who successfully restructured various matchstick problems showed increased fixations on the problem operators, which could be broken down to form the solution.

A similar conclusion was made with an eye tracking study performed by Grant and Spivey (2003) using Duncker's radiation problem. They found that participants fixating on the portion of the problem diagram needing to be re-represented (skin) was more common within people who successfully restructured the problem. As described above, participants have reported and performed reattempts during the impasse phase of solving, which is one possible explanation of what is happening internally during this time they spend staring in thought. If analyzing unsuccessful problem attempts is important for restructuring, and they are accessible on the screen, then it should be possible to use eye-tracking to examine how often and when participants are examining these past attempts.

Cognitive Reflection and Insight

Cognitive reflection, as measured by the Cognitive Reflection Task (CRT; Frederick, 2005), has been widely used in literature investigating analytical problem solving and heuristics-and-biases tasks. The questions are designed to categorize solvers between intuitive/impulsive solvers or reflective solvers by priming an initial incorrect strategy to reach solution that can be realized as incorrect through reflection so the true solution may be reached. Previous studies concluded with hypotheses that, because higher working memory capacity had been found to be a reliable predictor of higher CRT scores, this measure may be addressing the efficiency to which solvers use their available working memory resources within analytical problems (Stupple, Gale, Richmond, 2013). Participants must overcome the initial incorrect response that the questions are designed to activate. While not a direct measure of restructuring, this task involves elements of inhibition or reframing that are likely involved in the initial stages of restructuring. We hypothesized that those with higher cognitive reflection scores would also restructure their representations more often.

Current Study

The primary questions examined are whether solvers would benefit from access to unsuccessful problem attempts, and whether fixations on problem elements would differ across solvers. These questions were examined in one experimental condition by displaying three common initial attempts solvers have been shown to use at the onset of these problems (Common Attempts condition). These common attempts were generated by the experimenter based on previous studies' reports of the most common initial attempts on these problems. Three images were chosen that reflected common initial strategies on these problems and contained no elements of the restructuring required to solve the problems. Another condition provided access to each participant's own six most recent unsuccessful attempts (Own Attempts condition). Six attempts were chosen because it was the maximum number of images that could be presented while still being able to discern details about the chosen strategies. We expected those in the Common Attempts condition to perform better than those in the control condition (in which no attempts were shown) because they were presented with unsuccessful common strategies at the start of the problem rather than having to perform trial-and-error to rule the strategies out. Those in the Own Attempts condition were expected to show similar benefits but could experience more of an advantage due to their ability to examine more variable elements within their attempts because they were constantly being updated. This information was meant to be used to identify invariant components within each problem attempt that may lead to restructuring into a representation containing the solution.

This experiment was run in a large sample with a random subset of participants in the study being run with eye-tracking. Eye-tracking data were collected to determine if there were any fixation patterns that may predict successful restructuring and solving and to determine whether participants in the experimental conditions were referencing the available attempts. The results of the larger study will be briefly reported, but the focus of this paper is on the exploratory eye-tracking analyses. Gaze duration and fixation rates on different problem elements were examined across all conditions along with CRT scores. Because evidence of successful restructuring within a problem attempt can exhibit elements needed to fully solve the problem, we expected fixations from participants in the Own Attempts condition to be greatest on the problem attempts displaying successful restructuring. Because those with access to their unsuccessful attempts had more information available to analyze during the period of impasse, we expected them to spend less time overall gazing on what was termed "whitespace" or problem-irrelevant space during impasse. Finally, CRT scores were expected to serve as a significant predictor of restructuring and successful solving.

Method

Participants and Materials

A total of 306 participants (mean age 20, 54% female) completed this study for course credit or compensation of $20. According to a priori exclusion criteria, 25 participants were removed due to math performance on a working memory task falling below the 80% threshold and 27 were removed because they had seen two or more of the problems before. Sixty participants were randomly chosen to complete the study using an eye-tracker.

Computerized versions of three classic insight problems were created using the guidelines from the original papers discussing each problem (Nine Dot: Maier, 1930; Cheap Necklace: Silveira, 1971; Inverted Triangle: Tsai, 1987), and were implemented in Psychopy (Peirce et al., 2019). All problems were presented on the right half of the monitor, while the left half contained instructions and the unsuccessful attempts displayed to those in the experimental groups. A Tobii Spark monitor-mounted eye-tracker was used (sampling rate of 60 Hz) for the eye-tracking sample.

The Nine Dot problem was presented as an array of nine black dots (See Figure 1a). Participants were instructed to attempt to connect all dots with four lines. The problem reset when the end point of the fourth line was placed, or when participants pressed the "reset" button. There was a 15-minute time limit for this problem.

The Cheap Necklace problem contained four chains each with three links (see Figure 1b). Participants were instructed to reconstruct the chains to make a circle of chains similar to a necklace. They had a limited number of available moves, which was communicated in the form of "money," for them to spend to open and close links. At each new attempt, participants started with fifteen cents, which was displayed in the upper right-hand corner of their screen. Opening a link costed three cents and closing a link costed two cents, but it did not cost money to move links or chains. The problem reset when their money ran out, or when they pressed a "reset" button at the bottom of their screen. There was a 15-minute time limit for this problem.

The Inverted Triangle was presented as a grid of fifty-two squares containing ten circles in the shape of a triangle at the middle of the grid (see Figure 1c). The colors were updated as circles were clicked and moved to aid in keeping track of what had been moved, and each circle was numbered. Participants were tasked with moving circles such that the triangle was inverted but could only move three circles to do so. The problem reset when the third circle was placed or when the "reset" button was pressed. There was a 10-minute time limit for this problem.

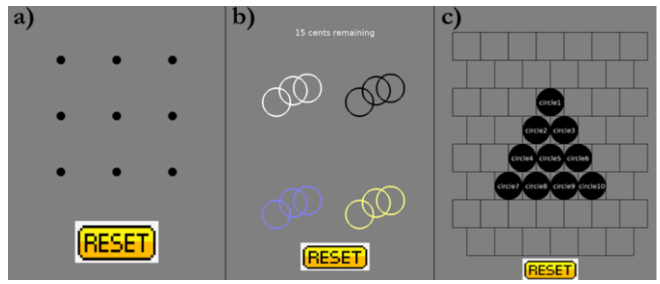

Figure 1: Three problems that participants solved. Problems were presented on the right side of the monitor, while the contents of the left side differed by condition. From left to right, the problems are (a) Nine Dot, (b) Cheap Necklace, and (c) Inverted Triangle.

The CRT was an adapted version (Toplak et al., 2014), of the original CRT (Frederick, 2005). This 7-item test featured questions meant to initially mislead the reader into responding with an intuitive answer, but required further reflection to answer the question correctly (e.g., "If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets?" [Correct answer = 5 minutes]). Scoring for this measure was the sum of correct answers.

Design and Procedure

Participants in the eye-tracking sample first completed a 13-point calibration. They then answered a demographics questionnaire, the CRT, and the Operation Span Task (Unsworth et al., 2009) in that order before moving on to the three problems. Results from the latter task will not be discussed in this study. Problem order was counterbalanced, and participants were given a short description of each problem they were about to complete and completed a short practice session.

All participants viewed the problem on the right half of their monitor, while the left half contained a condensed version of task instructions. Participants were randomly assigned to one of the three conditions. Those in the Common Attempts condition saw 3 unsuccessful attempts on the left side of the monitor (none of which contained any element of restructuring such as going outside the boundary of the dots in the Nine Dot problem), and those in the Own Attempts condition saw their six most recent attempts. All participants were instructed to attempt each problem as many times as necessary to solve or until the time limit was reached. The problem ended when the time limit was reached or when the program detected that the participant had solved the problem.

Results

The results of the main study will be reported briefly to provide some context for the analyses based on the eye tracking data. Solution rates were examined in a logistic mixed effects model predicting solution with condition, working memory capacity, and CRT scores as predictors. CRT (β = 0.54 [0.12], z = 4.49, p < 0.001) scores were positively associated with successful solving, but there was no evidence for a difference in solution rates based on access to unsuccessful attempts (χ^2 = 4.17, p = 0.12).

Each problem attempt made by participants was also coded for restructuring as defined by each of the problem's original studies. Restructuring in the Nine Dot problem was defined as lines extending beyond the border of the nine dots, in the Cheap Necklace problem was defined as the opening of a middle link and closing it on a link it was not originally attached to, and in the Inverted Triangle problem was moving at least two of the circles at the points of the triangle. Another logistic mixed effects model was used to examine rates of restructuring. It showed a positive effect of CRT scores on successful restructuring (β = 0.40 [0.20], z = 2.02, p = 0.04), but there was no evidence that the rate at which participants restructured differed based on access to unsuccessful attempts (χ^2 = 0.55, p = 0.76).

The lack of performance differences between the control condition and experimental conditions with access to unsuccessful attempts was not expected. The following results section will expand on these unexpected findings through exploratory analyses of the eye-tracking data for fixation patterns that do hold predictive power for representational change. The primary questions that were investigated were related to whether fixations on two major regions of interest were associated with CRT scores and successful solving.

Fixations on Problem-Irrelevant Space

Previous studies using eye-tracking with insight problems found that participants spent a portion of time during solving staring at problem-irrelevant space that was assumed reflective of impasse (Grant & Spivey, 2003; Jones, 2003). We were interested in whether time spent in this stage was associated with CRT scores or successful solving. When designing this study, whitespace was defined as any blank area on or off of the computer screen, so fixations on the current problem attempt, prior attempts, and additional problem elements were not considered whitespace in this model. It is also important to keep in mind that those in the control condition had a significantly larger amount of whitespace on the computer screen when compared to those with access to unsuccessful attempts. The purpose of this analysis was to assess whether people with access to unsuccessful attempts spent less time fixating on areas not relevant to the problem than people in the control condition.

The dependent variable within the first linear mixed effects model was the percentage of each person's total time on each problem that was spent fixating on whitespace. There were no significant differences between problems (χ^2 = 3.26, p = 0.12), conditions (χ^2 = 2.18, p = 0.34), or their interaction (χ^2 = 4.45, p = 0.35) on the amount of time participants spent fixating on problem-irrelevant space. To examine whether participants' ability to engage in cognitive reflection would serve as a reliable predictor of the time they engaged in fixating on whitespace, CRT scores were added to the model as a predictor. However, there was no identified association between CRT scores time spent fixating on whitespace (χ^2 = 0.30, p = 0.59).

A second analysis of participants' fixations on whitespace involved re-defining the term. If participants stopped solving for a period to assess their internal representation of the problem during impasse, they could still be staring at content on the screen while doing so. Cognitive reflection may also serve as a reliable predictor of the time they spend in this reflection. The previous analysis was performed once again, with the updated definition of whitespace including fixations anywhere except for the problem itself. This will be referred to as non-problem space. Figure 2 presents the proportion of total solving time spent gazing outside of the area where the problem was presented. This linear mixed effects model showed significant differences in proportion of total solve time spent fixating on non-problem space between problems (χ^2 = 29.11, p < 0.001), conditions (χ^2 = 9.00, p = 0.01), and their interaction (χ^2 = 15.20, p = 0.004). However, CRT scores were not related to this fixation time (χ^2 = 0.14, p = 0.70).

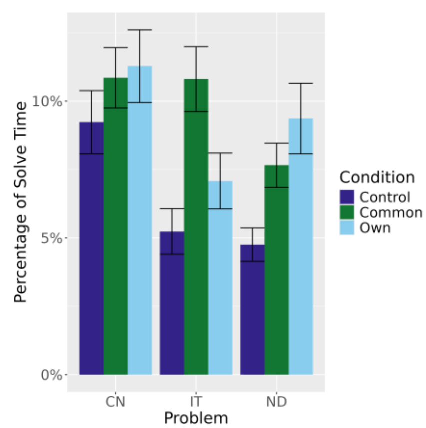

Figure 2: Average solve time that participants spent fixating on non-problem space. Fixations that did not fall within the bounds of any problem elements were averaged and grouped by problem and condition. Error bars indicate one standard deviation from the mean.

The differences between conditions were due to fewer fixations on non-problem space within the control condition when compared with those with access to Common Attempts

(β = -0.04 [0.01], t = -2.79, p = 0.007) and Own Attempts (β = -0.03 [0.01], t = -2.27, p = 0.03). As mentioned previously, these effects are most likely due to the additional information available on the screens of those in the experimental conditions. The differences between problems showed that fixations on non-problem space within the Cheap Necklace problem were higher than both Inverted Triangle (β = 0.03 [0.006], t = 4.64, p < 0.001) and Nine Dot (β = 0.03 [0.006], t = 4.61, p < 0.001). The interaction between problems and conditions was related to participants in the Common Attempts condition having higher fixations within the Inverted Triangle problem than those in both the Control (β = 0.06 [0.02], t = 3.70, p < 0.001) and Own Attempts conditions (β = 0.04 [0.02], t = 2.44, p = 0.02), while those in the Control condition solving the Nine Dot problem had lower fixations than solvers in the Common Attempts (β = -0.03 [0.02], t = -2.10, p = 0.04) and Own Attempts conditions (β = -0.04 [0.02], t = -2.96, p = 0.004).

Fixation Durations on Unsuccessful Attempts

A second set of analyses was concerned with whether participants in the experimental conditions showed different fixation durations on the available unsuccessful attempts. These analyses were restricted to the Common and Own Attempts conditions, and the proportion of time spent fixating on any of the available attempts was divided by each participant's total time spent solving. Thirty-six participants both met exclusion criteria and were assigned to one of the experimental conditions.

A linear mixed effects model was used to determine whether the condition, problem, and CRT score was related to the proportion of time participants spent looking at unsuccessful attempts. There were no differences in fixations identified between the Common and Own Attempts conditions (χ^2 = 0.001, p = 0.97), and there was no evidence that CRT scores predicted these proportions (χ^2 = 0.39, p = 0.53). There were significant differences in proportion of fixations between problems (χ^2 = 3.81, p < 0.001), which were due to higher fixations on Inverted Triangle attempts when compared to both Nine Dot (β = 5.97 [1.92], z = 3.11, p = 0.002) and Cheap Necklace (β = 5.68 [1.89], z = 3.00, p = 0.002) problems.

We next investigated whether the proportion of time spent fixating on unsuccessful attempts would be predictive of solving the problems, and these results can be seen in Figure 3. A logistic mixed effects model identified a significant effect of problem (χ^2 = 9.77, p = 0.007), CRT score (χ^2 = 4.32, p = 0.04), and the interaction between fixations and CRT scores (χ^2 = 4.20, p = 0.04) on solving but no main effect of fixations (χ^2 = 1.62, p = 0.20). The direction of these relationships indicates little about the effect of fixating on attempts across varying CRT scores on successfully solving the problem. However, participants who did not solve but scored higher on cognitive reflection spent more time analyzing their past attempts in an attempt to solve.

The final analysis of fixations on attempts was related to whether participants in the Own Attempts condition spent more time fixating on their own attempts displaying successful restructuring over their non-successful restructuring attempts. When exploring the results from this analysis, it is important to remember that there was a significantly larger number of attempts that did not display restructuring (2,870 out of 3,314 attempts) when compared to the number of attempts that did show restructuring (444 out of 3,314 attempts) across this study's sample. Nineteen participants both met exclusion criteria and were assigned to the Own Attempts condition.

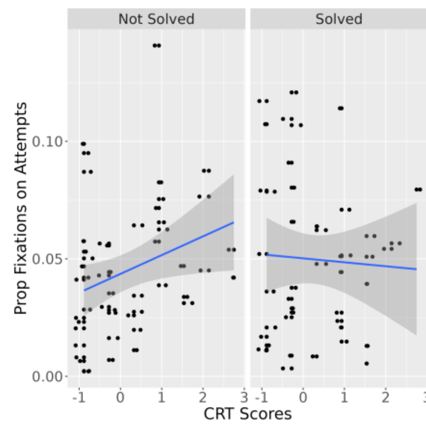

Figure 3: Proportion of solve time participants spent fixating on unsuccessful attempts. These results were restricted to participants in the experimental conditions.

A linear mixed effects model showed significant differences in these durations between problems (χ^2 = 6.31, p = 0.04), and this difference was due to participants solving the Inverted Triangle problem (β = 2.56 [1.03], t = 2.48, p = 0.02) spending more time fixating on their previous attempts that displayed restructuring over their non-restructuring attempts. There was no evidence found to support any differences in these fixations for the other problems.

Discussion

The primary purpose of this study was to further investigate eye-tracking data collected while participants solved some classic insight problems, with the major manipulation being different levels of access to unsuccessful problem attempts. This more detailed re-analysis of problem elements that both could and could not be operated on may then trigger the sudden reorganization of a participant's mental representation of the problem that now contains a solution. Terminology for this strategy was coined by Kaplan and Simon (1990) as the "Notice Invariants Heuristic," and was described as a natural strategy participants would employ following repeated failure at impasse. Fixations on unsuccessful attempts could be reflective of participants' attempts to restructure their representations using the Notice

Invariants Heuristic, and cognitive reflection may be related to either of these fixation patterns.

Results for this study can be categorized by fixations on problem-irrelevant space and fixations on attempts within the experimental conditions. The initial definition of whitespace analyzed in this study included any fixations outside the problem information and attempts, and there were no major differences identified between the proportion of total solving time participants spent fixating on whitespace and condition, problem, or CRT scores. A secondary analysis was performed with the assumption that participants may be exploring their internal representation while still fixating on some item on the screen, so non-problem space in this analysis included any fixations outside of the problem itself. This model showed differences in fixations between the control and experimental conditions, and also differed between problems and the interaction between problems and conditions. There were no differences found between participants with varying CRT scores. Fixations on non-problem space were highest within the Cheap Necklace problem, in the Common Attempts condition of the Inverted Triangle problem, and fixations were lowest in the control condition of the Nine Dot problem. This result shows evidence that the presence of prior attempts did encourage participants to look at them but were not successful in increasing rates of solution or restructuring.

The next set of analyses investigated fixations on unsuccessful attempts within the Common and Own Attempts conditions, with the expectation that participants with higher CRT scores would fixate on these attempts more than those with lower scores and participants in the Own Attempts condition would have longer fixations on their attempts that displayed restructuring. When analyzing the proportion of total solving time participants spent fixating on unsuccessful attempts, there were no identified differences in fixation times between the Common and Own Attempts conditions or across CRT scores. There were differences between problems. When investigating the effect of these fixations, conditions, problems, and CRT scores on successful solving, there were significant differences across problems and CRT scores as well as an interaction between proportion of fixations and CRT scores. This interaction indicates that among participants that did not successfully solve, participants with higher CRT scores spent more time fixating on the attempts. This result could indicate that participants with higher CRT scores were attempting to use the prior attempts to solve the problems but were not successful at doing so.

The final analysis was used to investigate whether participants in the Own Attempts condition had longer fixations on attempts displaying restructuring or non-restructuring, and results suggest that they spent longer fixating on restructured attempts only within the Inverted Triangle problem.

The results of this study are meant to serve as a preliminary investigation of the relationships between fixations and the proposed Notice Invariants Heuristic, and to inform future directions of this line of research. The present sample size of eye-tracking data is not sufficient to make any firm conclusions regarding the effect of CRT scores on fixations and solutions, but the lack of a relationship between CRT scores and fixations on non-problem space is a little confusing. If we are to assume that fixations on problem-irrelevant space are indicative of impasse and participants are reflecting on their own problem representation, why is the combination of higher CRT scores and higher fixations on previous attempts associated with unsuccessful solving? If participants with higher cognitive reflection were simply becoming fixated on the flawed representation perpetuated by access to the unsuccessful attempts, there would be an accuracy difference between the experimental and control conditions that was absent within this study. Perhaps CRT is measuring propensity to reflect but not capturing what is needed to restructure the representation or identify the invariants in the representation. Future analyses should categorize fixations as shorter or longer in order to more clearly differentiate between the encoding of extra problem information on the screen and longer durations that could be more closely related to impasse.

The current data is also being analyzed to determine if scanpath patterns are predictive of restructuring or solution. This analysis is ongoing, but capturing the order with which regions of interest on the screen were fixated on may be more informative than the amount of time that regions were fixated on. For example, if a prior attempt is fixated on followed by the region of the screen where active problem solving is taking place and the problem attempt shows evidence of restructuring, then the prior attempts that was fixated at that time and in that order may have been instrumental in solving the problem.

Future directions should utilize Bayesian versions of these analyses to determine the degree to which the null hypothesis is supported. These analyses would provide evidence for there being no differences, which would further inform the role that access to prior attempts may or may not have on restructuring within insight problems. Perhaps participants are not fully rehashing an attempt from start to finish, but re-examining how the previous strategies they employed affected their current representation of the problem. In this scenario, fully displaying all previous attempts may have only further fixated some participants that would have otherwise solved into their flawed representation.

Insight problem solving remains an elusive research area within cognitive science due to its debatably unconscious nature. Having access to unsuccessful previous attempts at an insight problem did not show a measurable effect within this experiment, but these results will inform future experiments investigating the potential existence of this effect. These future directions should explore different implementations of this idea before making any firm conclusions on the existence or absence of this heuristic.

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