Unveiling Analogical Reasoning Strategies: Insights from Eye Tracking in Four-Term Analogies

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Abstract

We applied eye tracking and semantically rich four-term analogies with a broad range of distractor types to investigate strategies of analogical reasoning. We adopted the operationalization of strategies proposed in previous eye-tracking studies and introduced an alternative, more fine-grained method of presenting gaze dynamics across a trial in a four-term analogy (A:B::C:D). Our analysis of fixations and transitions between Areas of Interest provided support for existing research findings, suggesting that the primary and most effective strategy when solving four-term analogies is the so-called projection-first strategy, which focuses on the source-domain relation and its generalization to the target domain.

Keywords: eye movements; analogical reasoning; four-term analogies; distraction; problem solving strategies

Introduction

Analogy making is a powerful method of problem solving. It consists of finding a correspondence between two situations and transferring information from a more familiar situation (a source) to a less familiar one (a target) (see Holyoak, 2012). Analogy making has been a topic of intensive research applying a variety of different methods and paradigms over the years. However, only recently application of eye tracking allowed for a deeper insight into a process of reaching the solution in the course of analogical reasoning. In contrast to behavioral data that provides information on the outcome of the reasoning, but does not tell us much about the process, eye tracking generates a precise record of what captured a participant's attention second by second before the response is made. Fixation areas and times are considered to be highly correlated with the informative value of particular regions (e.g., Rayner, 2012). In addition to fixation analysis, eye tracking allows for the analysis of the time-course of analogy making. Capturing its temporal organization provides an important insight into the role of analogy in key cognitive processes, such as problem solving (Gick & Holyoak, 1980; VanLehn, 1988), concept learning (Goldstone & Medin, 1994), language (Gentner & Kurtz, 2005; Lakoff & Johnson, 1980), and perception (Hummel & Biederman, 1992; Markman & Gentner, 1996).

Recent eye-tracking studies of analogical reasoning frequently applied so-called four-term analogies (Kroczek et al., 2022; Starr et al., 2018; Thibaut & French, 2016; Thibaut et al., 2022; Vendetti et al., 2017), which alongside scene analogies comprise the most popular paradigm in the field. Four-term analogies have a format: A is to B as C is to D. Object D is absent and needs to be found among several response options. Typically, in semantically-rich analogies, the set of response options includes the correct option as well as either a semantic distractor to C and two unrelated objects (e.g., Glady et al., 2017; Krawczyk et al., 2008; Thibaut & French, 2016), or a semantic distractor to C, a perceptual distractor to C, and one unrelated object (e.g., Starr et al., 2018; Whitaker et al., 2018; Vendetti et al., 2017). Introducing various distractors to an analogy task enhances its ecological validity because, in reality, various objects compete for attention during analogical reasoning. They are often based on perceptual similarity or semantic relatedness while not matching the proper relational structure. Such objects should be discarded during the construction of a relational system that effectively integrates the knowledge from the two domains (Gentner, 1983).

Strategies used during analogical reasoning are one of the central topics in research on analogies, especially when eye tracking is applied. Specifically, several recent studies aimed to verify the assumptions of computational models of analogical reasoning, mainly the projection-first and the structure-mapping strategy, by means of analyzing the eye movement patterns. These models differ primarily in terms of whether they prioritize the alignment between arguments playing the same role in the source and the target (i.e., the structure-mapping strategy) or whether they focus on the identification of relation in the source domain first (i.e. between A and B) and then apply it to the target domain (i.e. C and D; the projection-first strategy) (for reviews, see Gentner & Forbus, 2011; Gentner et al., 2001; Holyoak, 2012).

In previous eye-tracking studies (Starr et al., 2017; Thibaut et al., 2022; Thibaut & French, 2016; Vendetti et al., 2017), the following operationalization of strategies was adopted: in the case of projection-first strategy the reasoners should direct their gazes mainly to the A-B pair at the beginning of the trial, and later switch their gazes to C and the target. In contrast, the structure-mapping strategy would be characterized by a high number of saccades between A and C at the beginning of the trial, and between B and the target at later stages. In the first attempts to grasp

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the time-course of analogical reasoning by means of eye tracking, each analogy trial was divided into three time slices, and the saccades at the beginning, in the middle, and at the end of a trial were analyzed separately (Thibaut, et al., 2011; Thibaut & French, 2016). Based on the number of transitions between areas of interest (AOIs) in each time slice it was concluded that adults organize their search according to the projection-first strategy mostly. Instead of slicing, Vendetti et al. (2017) proposed a classification algorithm assigning trials to strategies based on the initial fixations and the total number of transitions between AOIs. In line with the previous studies, they reported the projection-first to be the most common (49.6% of classified trials) and effective among the three tested strategies. However, a substantial portion of trials (34.2% of classified trials) has been assigned to the structure-mapping strategy, but in this case there was no significant correlation with accuracy. The last tested strategy called semantic-constraint was the least frequent of all the three strategies (16.2% of classified trials). It was characterized as organized around C with little or no interest in the A-B pair. Semantic-constraint strategy was negatively correlated with accuracy. In the later study this strategy was found to be mostly used by children, likely because they focused strongly on the overarching goal – to find the picture that goes with C – and as a consequence, they ignored the sub-goal to analyze the A-B pair (Starr et al., 2018). Importantly, the classification algorithm worked according to the 'winner-takes-all' rule (trial was assigned to a particular strategy if the score was higher than the score for the other strategy), and the temporal dynamics of the trial was not considered, as focus was on the early gazes only and the general number of transitions.

Recently, Thibaut et al. (2022) extensively investigated the time-course of processing simple vs. complex analogies in the four-term word analogy and scene analogy tasks. They splitted each trial into three identical time slices and by means of machine learning techniques identified the patterns of transitions that best predicted the output of a trial (either incorrect or correct) as well as its difficulty level (simple or complex). The main conclusion from their study was that all analogy formats, regardless of items' difficulty, were solved according to similar global search patterns, largely characterized by the projection-first approach.

In our recent study (Kucwaj et al., 2022), we proposed a different perspective to examine whether object B is considered during the response selection stage. We introduced various distractors to both C and B among the response options. The response selection patterns suggested a general immunity to distractors to B, which was inconsistent with the expected outcomes if the structure-mapping strategy were applied. However, the question of whether distractors to B were considered but successfully discarded, or whether they were simply ignored (not attended to at all), remains unanswered, as eye gazes were not recorded in that study. This issue warrants further investigation, particularly given that we have used a diverse range of distractors, including perceptual, categorical, semantic, and relational distractors to both C and B within one task. Such an extensive spectrum of distractors together with eye-tracking would offer valuable insights into participants' reasoning mechanisms.

In summary, various methods of analyzing eye gazes in analogy generally suggest that people tend to consider the source domain first, and only after identifying the relation linking A and B do they apply it to find D, which is related to C as B is related to A. However, employing a task with a broad range of distractors followed by a more dynamic approach to eye tracking revealing the time course of the process, is needed.

Research goals

Previous attempts to identify the strategies employed in solving four-term analogies via eye-tracking might have been insufficient, primarily due to a substantial reduction of the respective process dynamics by using a few time slices, or algorithms implementing the 'winner takes all' rule. Consequently, in the present eye-tracking study, we applied Kucwaj et al.'s (2022) semantically-rich four-term analogy task to investigate whether distractors rarely selected in prior studies (e.g., distractors to B, perceptual lures) would be either rejected after consideration (indicated by fixations on these options) or simply ignored by reasoners (no respective fixations). Our goal was to determine whether behavioral data (selection rates for each option) aligned with eye-tracking data (gazes to each option). Furthermore, we introduced a novel, fine-grained approach to analyzing transitions between consecutive AOIs, offering a more dynamic perspective, compared to previous studies. This approach, combined with the examination of fixations on distractor options, aimed at more unequivocal evidence supporting the predominance of the projection-first strategy in healthy adult participants.

We aim to plot transitions between AOI's in time in order to see whether the transitions A-B and C-choice options, which correspond with the projection-first strategy, are more prevalent as compared to the transitions A-C and B-choice options, which would correspond to the structure-mapping strategy, in line with the assumptions made in previous eye tracking studies (Starr et al., 2017; Thibaut et al., 2022; Thibaut & French, 2016; Vendetti et al., 2017). Finally, we intend to conduct correlation analysis to determine whether using a particular strategy of solving four-term analogies predicts accuracy.

We expected that the introduction of novel distractor types to the four-term analogy task combined with the precise analysis of gaze dynamics across its trials would provide important knowledge on the cognitive processes and strategies underlying four-term analogical reasoning.

The study

Participants

The total sample included 54 people (32 females; aged 18 to 32 years, M = 23.7 y, SD = 3.9 y). All participants were recruited from the general population via internet adverts and paid an equivalent of 12 USD in local currency. All participants signed a written consent to participate, were screened for normal vision and no history of neurological problems, and were informed that they could stop the experiment and leave the lab at will. Data was anonymized.

All other procedural aspects of the study conformed to the WMA's Declaration of Helsinki.

Four-term Analogy Task

The task consisted of 40 four-term analogies, 20 without distraction and 20 with distraction. The order of items was fully random. Each problem had the structure A is to B as C is to D. Object D was absent and participants were asked to choose the response out of seven options. All stimuli were pictures of common objects. In the non-distraction condition, the response options included the correct answer and six unrelated objects. In the distraction condition the response options included the correct answer and six distractors: semantic distractor to C, categorical distractor to C, perceptual distractor to C, semantic distractor to B, categorical distractor to B, and perceptual distractor to B. The perceptual distractor was defined as an object that shares a similar shape and color to B/C (e.g. green apple and green ball). The categorical distractor was defined as an object that belongs to the same semantic category and has a similar, but not identical shape or color to B/C (e.g. a pot and a frying pan). The perceptual similarity was weaker in this case than for the perceptual distractor. The semantic distractor was defined as an object associated with B/C in terms of shared domain or occurrence (e.g. fishing rod is a semantic distractor to fish). An instruction and two problems were provided with information which option is the correct one and why. It was emphasized that more than one object may seem to go with C but participants were asked to choose the only one that was definitely related to C in the same way that B is related to A. The response was given by clicking a picture. For each problem, the maximum time for response was 20 seconds. The task was preceded by two training problems with feedback. Each trial was preceded by a fixation point. Fig. 1 presents an example of A:B::C:D analogy.

Eye tracking apparatus

Eye movements during semantically-rich four-term analogies were recorded using Eyelink Plus 1000 (SR Research, Canada), with a sampling rate of 1000 Hz. The experiment took place in an isolated cabin with low lighting. The eye tracking device was situated under the computer screen. A chin rest was used to hold the participant's head still. Eye calibration was applied at the beginning of the eye tracking procedure with additional drift validation between trials. The entire procedure was supervised through a camera by a research assistant who was sitting outside the cabin. Eye tracker returned two key types of data: the times of separate fixations on AOIs and the number of transitions between particular locations on the computer screen. Each AOI was delimited spatially by the light gray square (see Fig. 1).

Overall pattern of gazes across a trial

Our fixation analysis aimed to present the percentage of time that the participants spent fixating on each of the possible AOI. We defined ten AOIs, specifically: objects A, B, C, and the target as well as six incorrect response options (either the distractors in the distraction condition or the unrelated objects in the non-distraction condition). For each trial of each participant and each of the 10 possible AOIs, the time of the saccades was summed and then divided by the duration of the trial. The resulting value reflected the proportion of the fixation duration to a given AOI. These values were then averaged and are presented in Fig. 3.

For the transition analysis, nine key transitions were identified, specifically: transitions between object A and B, A and C, B and C, as well as between A, B, C and the target, and between A, B, C and the other options (either the distractors in the distraction condition or the six unrelated objects in the non-distraction condition), the latter summed and divided by six to ensure comparability between AOIs of different sizes. We were mainly interested in observing two patterns of transitions: (a) the ratio of transitions between A and B (i.e., the source pair) and between A and C (i.e., the arguments playing the same role in the source domain and the target domain) as well as (b) the ratio of transitions between C and choice options as compared to transitions between B and choice options, in order to identify which object (C or B) is the primary object of reference during response selection.

Figure 1: Sample item of the Four-term Analogy Task. The A:B::C:D? problem (top) to solve: puddle:rain boot::hot pot:? Response options (bottom) are the following: an oven mitt - correct response, a gas burner - semantic distractor related to C, a frying pan - categorical distractor related to C, a basket - perceptual distractor related to C, an umbrella - a semantic distractor related to B, a boot - a categorical distractor related to B, a chess pieces - a perceptual distractor related to B. The order of response options was fully random across all trials in the study.

We treated saccades bidirectionally, meaning that in the case of transitions of a given category (e.g. A to others) both saccades starting in A and ending in any of the "other" options are included, as well as those that started in any of "other" options and ending in A. The duration of each saccade was summed separately for each category and each second. Then this value for each category was divided by the sum of the duration of all saccades in a given second, which resulted in the percentage of saccades of each category within the second. Fig. 4 presents transitions within nine categories in the correct trials (a) in the distraction and (b) in the non-distraction condition. We did not plot the incorrect trials because of the very low number of incorrect responses.

Results

Behavioral results

Mean accuracy in the Four-term Analogy Task equaled $M = 87\%$ ($SD = 33\%$, range 47%-100%). Accuracy in the non-distraction condition equaled $M = 94\%$ ($SD = 20\%$, range 20%-100%), with distraction it equaled $M = 79\%$ ($SD = 47\%$, 75%-100%), and their difference was significant, $t(53) = -7.03$, $p < 0.001$, Cohen's $d = 1.16$. The distractors related to B (semantic, categorical, perceptual) and the perceptual distractors related to C were selected very rarely, making from 0.4% to 8.8% of all the errors committed, depending on the distractor type (21.3% in sum). The semantic and categorical distractors related to C comprised 58.2% and 20.4% of all the errors committed, respectively (see. Fig. 2).

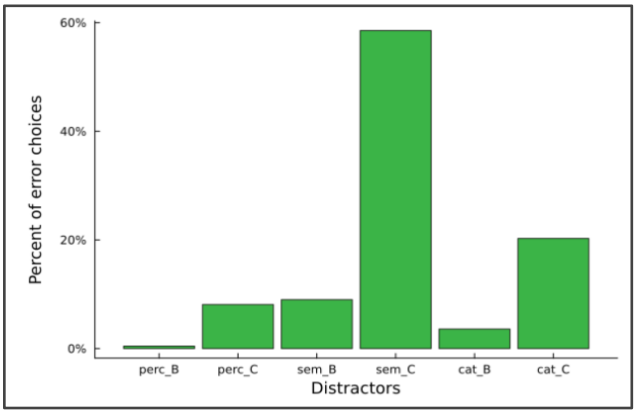

Figure 2: Percentage of error choices in Four-term Analogy Task, computed as the proportion of the number of choices of each error option (perceptual distractor to B and to C, semantic distractor to B and to C, and categorical distractor to B and to C) in the number of all errors committed.

Proportion of time spent fixating on AOIs

Figure 3a presents a proportion of time spent fixating on each AOI in correct trials in the non-distraction condition. Participants spent most of the time fixating on A, B, C, and the target. In the case of the remaining AOI's, participants evenly distributed fixations across all the unrelated objects. Data presented on the histogram shows that values around 5% might be interpreted as a baseline time of inspection of objects which are relatively easily ignored while searching for the target. There were very few incorrect trials in the non-distraction condition, so they were not analyzed.

Figure 3b presents a proportion of time spent fixating on each AOI in correct trials in the distraction condition. The pattern of fixations is similar to the one presented in Figure 3a, which suggests that, when participants were able to infer the relation between the source and the target domain, they did not fixate on options other than the correct answer.

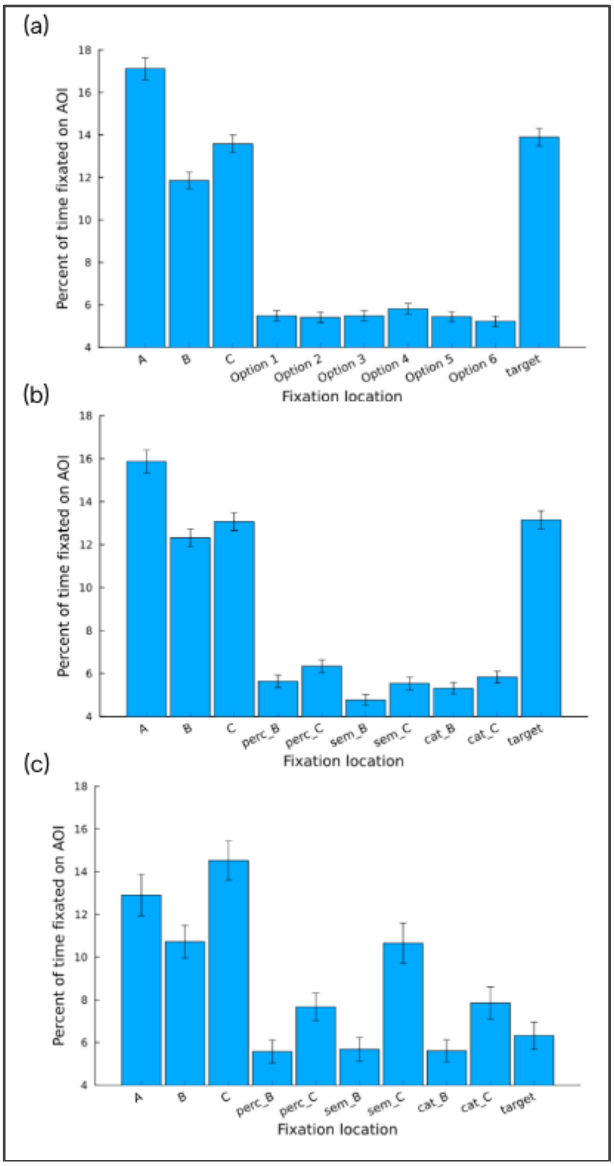

Figure 3: Percent of time spent fixating on each AOI in (a) the correct trials in the non-distraction condition, (b) the correct trials in the distraction condition, and (c) the incorrect trials in the distraction condition of Four-term Analogy Task. Time spent fixating on unrelated objects in the non-distraction condition (Options 1-6) equaled 5.47% on average and it was interpreted as a baseline time of option inspection. Bars indicate 95% confidence intervals.

Figure 3c presents a proportion of time spent fixating on each AOI in incorrect trials in the distraction condition. Firstly, the fixation proportion for each distractor to B equaled around 5.6%, meaning that participants analyzed these options for a similar amount of time as they analyzed unrelated objects in the non-distraction condition. In other words, these objects, which were intended to introduce distraction, actually did not work as distractors (i.e., they were easily ignored). Secondly, participants fixated on the perceptual distractor to C, which was rarely selected (8.4% of all errors), comparably as they fixated on the categorical distractor to C (20.4% errors), suggesting that perceptual distractors to C were indeed considered (not simply ignored as distractors to B), but then were relatively easily rejected.

Transitions between AOIs

Fig. 4a and 4b present transitions between five aforementioned AOIs (i.e. A, B, C, target, other) for the correct trials in the non-distraction condition and the distraction condition, respectively (nine categories of transitions). Overall, in both conditions, we observed the predominance of transitions between A and B over transitions between A and C, as well as the predominance of transitions between C and the target over transitions between B and the target suggesting that the projection-first strategy is the leading one. Nevertheless, we are not able to make a firm conclusion on significant differences between the strategies on the basis of this plot due to relatively high variance of saccade movements leading to high disparity of confidence intervals. Consequently, we aggregated transition occurring during the first 11 seconds of each test item, which were related to each of the two strategies (A-B and C-choice options transitions for the projection-first and A-C and B-choice options transitions for the structure-mapping). Fig. 5 shows the mean number of saccades attributed to each strategy for correct trials in the distraction (5a) and in the non-distraction condition (5b). In the case of distraction condition the projection-first strategy (M = 27.77) significantly dominated over the structure-mapping strategy (M = 10.20), $t(68.89) = 9.75$, $p < .001$. Similarly, in the non-distraction condition the projection-first (M = 27.29) was applied to a further extent than the structure-mapping strategy (M = 11.11), $t(74.37) = 11.35$, $p < .001$.

Lastly, to examine whether the strategies predict the accuracy in the task we calculated an indicator of the prevalent strategy, the strategy use ratio (no. of transitions for the projection-first divided by no. of transitions for the structure-mapping strategy). We computed Pearson correlation between the strategy use ratio and accuracy, separately for the distraction and the non-distraction condition. In the case of both conditions, we found substantial correlations, $r = .41$, 95% CI [.16, .61], $t(51) = 3.23$, $p = .002$, and $r = .50$, 95% CI [.27, .68], $t(52) = 4.21$, $p < .001$ respectively, suggesting that the larger use of the projection-first strategy by a participant, the more accurate solutions to the four-term analogies they delivered.

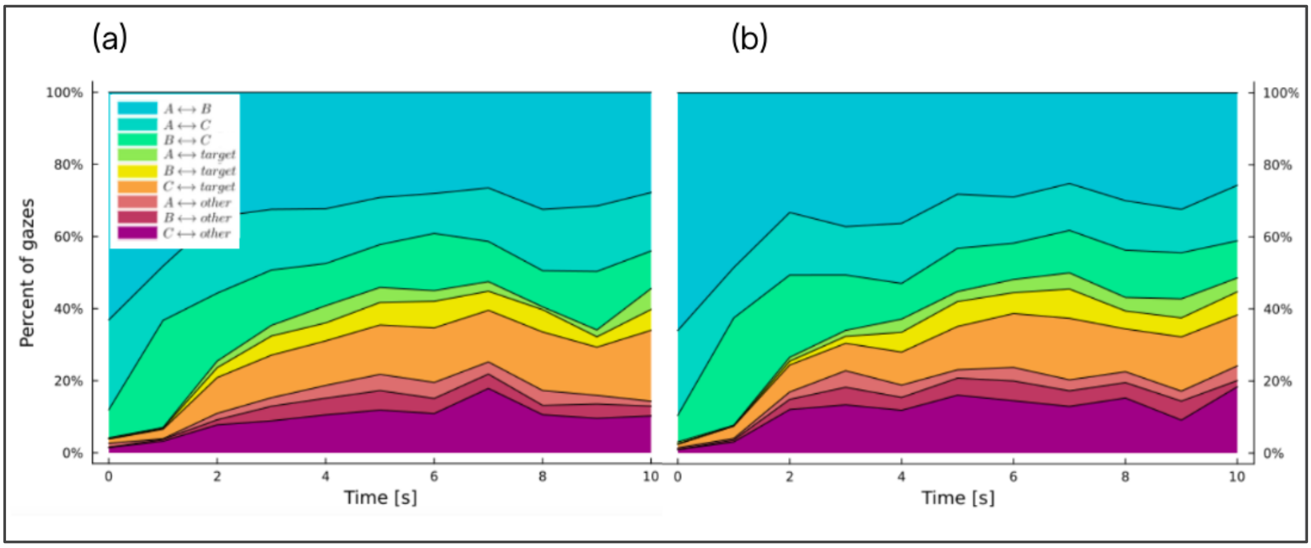

Figure 4: Transitions between objects A, B, and C as well as between A, B, C and the target and the other choice options in (a) the distraction and (b) the non-distraction condition. See text for details. The first 11 seconds of trial are shown, which make up 95.5% of all saccades. The remaining 4.5% were unevenly dispersed above 11th second, resulting in a very noisy and uninterpretable signal.

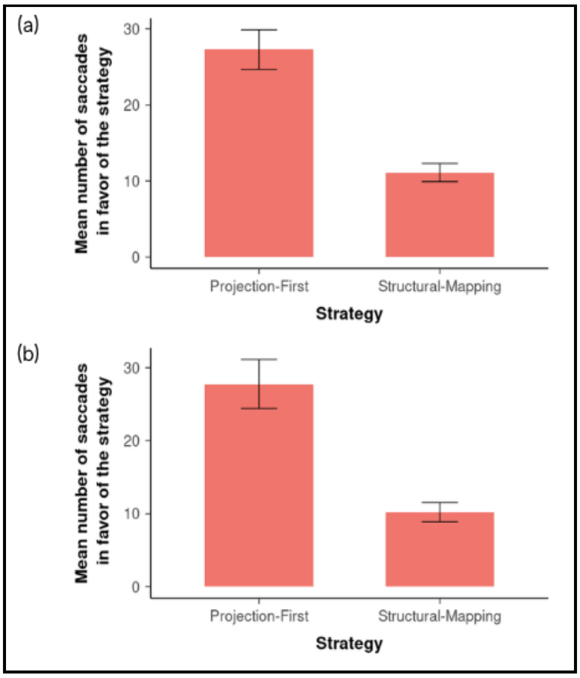

Fig. 5. Mean number of saccades corresponding to the projection-first (sum of transitions: A-B and C-choice options) or structure-mapping strategy (sum of transitions: A-C and B-choice options) in the correct trials (a) of the non-distraction and (b) of the distraction condition.

Discussion

The present study comprehensively examined the pattern of fixations and eye movements in semantically-rich four-term analogies, encompassing a broad spectrum of distractor types. Our goal was to propose a novel method for analyzing transitions between AOIs to provide unequivocal support for existing studies on strategies of solving four-term analogies in the healthy adult sample. Our analysis, which decreased data reduction seen in previously employed methods (i.e. classification algorithms, analysis of transitions in time slices), by analyzing the process second by second, seems to confirm that the projection-first strategy dominates within the healthy adult sample in four-term picture analogies. We based this conclusion on two key observations.

Firstly, our analysis of fixations demonstrated that distractors related to B do not constitute a significant source of information at the stage of searching for the target option. All three distractors to B received as much attention as any unrelated object in the non-distraction condition (at the baseline level of around 5.5%). Interestingly, perceptual distractors to C, which were scarcely selected, were analyzed significantly more frequently (7.65% of fixation time) compared to the baseline level. This finding further supports the notion that C, rather than B, is the most important reference object in the response selection process.

Second, aggregation of saccades corresponding with each strategy to separate bins (e.g. the A-B transition, and all saccades from/to C) allowed us to conclude that in our healthy adult sample the projection-first strategy was used to a larger extent, as compared to the structure-mapping strategy. Our work provided a new source of evidence for supporting the former strategy.

Lastly, we showed that the use of projection-first strategy relative to the structure-mapping strategy, is positively correlated with the accuracy of reasoning by analogy in the four-term analogy task. Our participants used this strategy more frequently than the other strategy, because the former was most likely a more effective strategy. This result is consistent with previous studies that have associated the projection-first strategy with accuracy (Vendetti et al., 2017; Starr et al., 2018).

The study had some limitations. Primarily, we applied only one paradigm, specifically four-term analogies, which on the one hand were not particularly challenging for healthy, young adults, as suggested by short reaction times and high accuracy. It seems that the (simple) relations present in the task were relatively easy to infer, and the task cannot provide much insight into how the strategy depends on the complexity of the problem or the level of familiarity with the problem domain. On the other hand, a substantial number of participants were caught by several distractors, so at least the distraction condition posed some difficulty to the participants. Definitely, future studies on strategy use should include more difficult variants of the four-term analogies and most importantly other analogy tasks.

Conclusions

By applying the novel precise method of presenting the dynamics of transitions between elements of the four-term analogy, as well as by introducing the distractors to B alongside the distractors to C, the present study provided strong support for the projection-first strategy as the most likely way for solving this kind of analogy problems. In consequence, the study deepened our knowledge on the strategies used in analogical reasoning. This knowledge can inform future models of analogy-making processes. Methodologically, this work shows that eye tracking is a highly useful method of revealing cognitive processing taking place during complex cognitive tasks.

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