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Abstract

Three leading analogical reasoning paradigms: scene analogies and pictorial A:B::C:D analogies (both semantically-rich) and geometric analogies (semantically-lean) were solved by 251 participants. Pictorial analogies included four types of lures among the response options (perceptual, categorical, semantic, relational). Moreover, distractors related to both B and C were introduced. Additionally, a fluid intelligence test was applied to examine the relationship between the paradigms and general reasoning ability. Results indicated that: (a) objects semantically related to C yielded the strongest distraction in four-term analogies, categorical and relational distractors yielded moderate effects, perceptual distraction was negligible; (b) distractors related to B were relatively easy to ignore, suggesting that C is the primary object of reference during the response selection; (c) whilst the three tasks correlated significantly without control for fluid intelligence, only the semantically-rich tasks did after fluid intelligence was accounted for, suggesting a certain common mechanism, independent of fluid intelligence, underlying the two.

Keywords: analogy; reasoning; distraction; mapping

Introduction

Reasoning by analogy – the ability to draw conclusions about one situation on the basis of relational similarity to another situation – constitutes a fundamental mechanism underlying intelligent and adaptive behavior (Gentner, 2003; Penn, Holyoak, & Povinelli, 2008). Making analogies is prevalent in human cognition, playing an important role in such domains as problem-solving (Gick & Holyoak, 1980; VanLehn, 1988), language use (Lakoff & Johnson, 1980), and concept learning (Goldstone & Medin, 1994). It requires a certain level of competence in relational representation and inhibitory control (Doumas, Morrison, & Richland, 2018; Gentner, 2003; Richland, Morrison, & Holyoak, 2006). Reasoning by analogy, however, does not always lead to valid conclusions. Specifically, certain conditions, for instance distraction, can disturb analogical mapping.

Analogical reasoning comprises finding correspondence between two situations and subsequently transferring information from the more familiar situation (*source*) to the less familiar one (*target*). Most importantly, the mapping of one situation onto another must comprise the relational structures underlying both situations. A surface similarity, such as perceptual resemblance and semantic overlap, is neither sufficient nor necessary for valid analogy, albeit when analogous domains are closely related and their surface similarity is congruent with their relational structure, source retrieval is easier and the process is less error-prone. Otherwise, when perceptually/semantically similar objects play different relational roles, surface similarity may distract from the key relational correspondence, leading to invalid mapping (e.g., Chuderska & Chuderski, 2014; Gentner & Toupin, 1986; Richland et al., 2006). The present study was devoted to increasing our understanding of the way the human mind copes with distraction during analogical reasoning. To this end, two widely used analogy tasks were modified.

Methods to investigate analogical reasoning

Two hallmark paradigms to study reasoning by analogy consist of scene analogies and pictorial four-term analogies. In scene analogies, two pictures (scenes) presenting everyday situations (e.g., giving, helping, etc.) are introduced to the reasoner. One object is highlighted in the source scene. The task is to identify an object in the target scene that plays the same relational role as the one marked in the source scene. Mapping of relations and their arguments is required to solve the problem. Pictorial four-term analogies have the A:B::C:D structure, meaning that the relation linking object A and object B applies to object C and object D. For example, for the analogy *wheat:bread::tomato:ketchup* the underlying relation is *material:product*. To solve the problem, one must select object D (*ketchup*) from the response options set.

Scene analogies and pictorial four-term analogies are both intuitive and their instruction is relatively easy to follow, which contributes to their vast popularity in studies on children (e.g., Richland & Burchinal, 2013; Richland et al., 2006) and clinical groups (e.g., Krawczyk et al., 2008, 2010, 2014; Kucwaj & Chuderski, 2020). Familiar content (everyday situations and objects) makes these tasks ecologically valid, as they resemble real-life problems. Nevertheless, the course of the analogical reasoning process varies between the paradigms. A crucial difference between the, rather complex, scene analogies and the simpler four-term analogies, the former depicting several objects and the latter constructed of isolated objects, becomes significant at the mapping stage. In the case of scene analogies, the comprehensive mapping of relations and their arguments is essential. It is especially important when similar or identical objects from the source play different relational roles in the target. By contrast, in the four-term analogies, the alignment structure and arguments are already provided, and the arguments need not be extracted from a broader context. Therefore, a full-blown mapping is not necessary.

The third popular method of studying analogical reasoning is geometric analogies. Unlike the two already discussed analogies, it is semantically lean. It also has the four-term structure, but as geometric shapes yield no associated meaning, the reasoner must primarily rely on abstract reasoning. Patterns A and B make the first pair in which shapes share some common features but differ in some other characteristics, such as size, color, thickness, orientation, etc. The task is to analyze A and B, identify the changing features therein, and find such a D that is related to C in the same way as B is related to A. In the case of difficult items, several features undergo transformation within each pair, making the task very complex and heavily loading working memory. Geometric analogies are often applied as a measure of fluid intelligence (e.g., Chuderski, 2013; see Mackintosh, 1998).

Distraction during analogical reasoning

Pictorial four-term analogies are widely used to study distraction during analogical reasoning, by means of applying semantic and/or perceptual lures to object C among the response options (e.g., Krawczyk et al., 2008; Kucwaj & Chuderski, 2020). For example, for an analogy *wheat:bread::tomato:?* the response options could include *ketchup* (the correct answer), a *red ball* (perceptual distractor to C – an object that shares the same shape and color as tomato), a *garden patch* (semantic distractor to C – an object that is semantically related with tomato), and unrelated object (a kind of control condition). In the most frequent task variant, the response options comprised the correct answer, semantic distractor, and two unrelated objects (e.g., Glady, French, & Thibaut, 2017; Krawczyk et al., 2008), alternatively, they comprised the correct answer, semantic distractor, perceptual distractor, and an unrelated object (e.g., Starr, Vendetti, & Bunge, 2008; Whitaker, Vendetti, Wendelken, & Bunge, 2018).

For instance, it was found that patients with frontotemporal lobar degeneration were less accurate in the distractor condition of the analogy task, as compared to healthy controls who easily ignored distractors (Krawczyk et al., 2008). In children samples, analogies with semantic lures among response options were found more difficult than problems with perceptual lures (Thibaut, French, Venanza, Gérard, & Glady, 2011). Moreover, children who performed worse in inhibitory control tests were more likely to choose distractors.

However, creating distractors that perfectly match assumed criteria (e.g., of being a semantic distractor), especially in semantically rich tasks, is not an easy task. It happens that objects determined as perceptual lures have characteristics of both perceptual and semantic distractors. For example, in Krawczyk et al. (2008), a *gavel* was used as a perceptual distractor to a *hammer*. These two objects have more in common than simply appearance: both can be categorized as a tool and used in a similar way (to hit things), etc. In some languages (e.g., French), both have even the same name. Thus, in order to study distraction precisely and univocally, the response options should be designed carefully, with semantic distractors not resembling targets perceptually, and perceptual distractors belonging to a distinct category.

We also propose that the third distractor type should be defined alongside the perceptual and semantic distractors. Specifically, objects related to C both semantically and perceptually seem to comprise categorical distractors. For example, a *red bell pepper* could constitute a categorical distractor for a *tomato*, as it both belongs to the same semantic category and resembles the tomato perceptually.

Perceptual, semantic, and categorical lures do not exhaust all potential sources of distraction. Consider the following analogy: *rose* (A) is related to the *sun* (B) as a *rabbit* (C) is related to *?*. One may identify the relation correctly (*source of energy*), but make a mistake at the stage of selection, choosing a *pizza,* which is a type of food and provides energy, but typically is not suitable for rabbits. This type of lure, which we call a relational distractor, constitutes a potential distraction to the target. Selecting this type of response option would suggest that a mistake has been made at the late stage of reasoning after the key relation had already been found.

In scene analogies, the effects of distraction are typically studied by manipulating their level of so-called transparency, which refers to a degree of perceptual and semantic similarity between non-corresponding objects. Specifically, the lowest transparency occurs in cross-mapping, when similar or even identical objects play different relational roles in both scenes (so mapping has to proceed despite this similarity, ignoring it). For instance, when a boy is chasing a dog in the source scene but is himself chased in the target scene (or just stands by when two other actors take part in chasing), it would be a mistake to match the boys together as their relational roles differ in both scenes (chasing vs. being chased/standing by). Numerous studies showed that reasoning in scene analogies is impaired by low transparency in the case of children (Gentner & Toupin, 1986; Richland, Morrison, & Holyoak, 2006), patients with brain injuries (Krawczyk et al., 2010), and even healthy adults (Chuderska & Chuderski, 2014).

Research questions

On the one hand, studying distraction caused by strong but irrelevant semantic and perceptual overlaps, occurring in real-life situations, requires semantically rich context-embedded analogy problems. On the other hand, geometric analogies can be considered a relatively purer method to investigate analogical reasoning per se, as no specific domain knowledge and vocabulary are needed to solve them, and therefore reasoning performance cannot be affected by ineffective retrieval and other processes beyond analogy. Moreover, geometric analogies provide an objective way to manipulate their difficulty level, by varying the number of shapes and shape transformations (e.g., Hosenfeld, Van den Boom, & Resing, 1997). Examining the extent to which the three hallmark analogy tasks tap into either overlapping or divergent processes can be potentially illuminating.

We applied all three analogical reasoning paradigms as well as the Raven's Advanced Progressive Matrices (RAPM; a widely acknowledged measure of fluid intelligence) to a large sample of participants in order to investigate the effects of distraction on performance in semantically rich analogies as well as to examine the mutual relationships of four-term analogies, scene analogies, geometric analogies, and the fluid intelligence test, to date applied in isolation. Importantly, we designed a novel four-term analogy task to precisely investigate the established (perceptual and semantic) and the new distractor types (categorical and relational). Moreover, we introduced not only distractors to object C, as studied so far, but also applied distractors to object B, in order to track a precise mapping strategy adopted by the participants. Together with the introduction of cross-mapping in scene analogies, our semantically rich analogies had the potential to provide a comprehensive picture of the role of distraction in analogical reasoning as well as of its relation with more abstract types of reasoning.

Method

Participants

A total of 253 volunteers were recruited via the internet. All gave written consent, were screened for normal or corrected-to-normal vision and no history of neurological or psychiatric disorders, and were informed that they could stop the experiment at any time. All other procedural aspects of the study conformed to the WMA's Declaration of Helsinki. Two participants were excluded from the analysis due to a very short mean reaction time (RT) in computerized analogical reasoning tasks, suggesting random responding (mean RT less than 4 s). The final sample included 251 people (175 women, aged 18-41, $M = 23.9$ years, $SD = 4.92$ years).

Pictorial Analogy Task

It consisted of 40 four-term analogy problems. Each problem had the A:B::C:D format. All stimuli were pictures of familiar objects. Participants were asked to consider an analogy according to the rule "A is to B as C is to D". An example was provided. The task was to choose D from a set of possible response options to construct a valid analogy. Participants were said that more than one object may seem to go with C, but they should choose the one and only that is related to C precisely in the same way that B is related to A. The ten response options comprised the following options: the correct answer, relational distractor, semantic distractor to B and C, categorical distractor to B and C, perceptual distractor to B and C, as well as exact copies of objects C and B. In line with the above-presented definitions (and examples), the perceptual distractor was an object of a similar shape and color as B/C; semantic distractor was an object associated with B/C in terms of the shared domain, function, or occurrence (e.g., *tomato* and *garden patch*). A categorical distractor was an object that belonged to the same category and had a similar shape or color as B/C; a relational distractor was an object that could potentially constitute an argument for the relation in analogy, but not when the specific object (C) played the role of agent. Exact copies of B and C were introduced to monitor potentially thoughtless responding (e.g., random guessing). Fig. 1 presents an example item from a pictorial four-term analogy task.

Figure 1: A sample item of the Pictorial Analogy Task. The A:B::C:D? problem to solve is: *puddle:rain boot::hot pot:?* Response options (below the problem) are the following: (1) *an oven mitt* is the correct response, (2) *a gas burner* is a semantic distractor related to C, (3) *a frying pan* is a categorical distractor related to C, (4) *a basket* is a perceptual distractor related to C, (5) an exact copy of C, (6) *an umbrella* is a semantic distractor related to B, (7) *a boot* is a categorical distractor related to B, (8) *a chess piece* is a perceptual distractor related to B, (9) *a rubber glove* is a relational distractor, (10) an exact copy of B. Actual order of options was fully randomized for each participant.

The order of trials was randomized for each subject. A pilot study ($N = 61$) verified the validity of consecutive problems and response options (non-optimal items were then improved). It also confirmed that the number of response options (ten) neither was problematic for the participants nor prevented the high solution rate to be observed (85% correct).

Scene Analogy Task

This task consisted of 36 problems from the Scene Analogy Task originally developed by Chuderska and Chuderski (2014). Participants were instructed to explore the left scene in which one object was pointed at by an arrow or encircled by a red rim. The task was to find an object in the right scene which played the same role in a situation as the flagged object in the first scene. Half of the problems involved cross-mapping, defined as a condition when a categorical distractor (according to the definition from the Pictorial Analogy Task: an object similar but not identical perceptually, sharing the same semantic category) was present in a target scene but played a different relational role than the similar object in a source scene. Therefore, the target-distractor was competing for the reasoner's attention. What is important, in the Scene Analogy Task applied in this study, a distracting object was always involved in a relational structure, which is not typical for scene analogies. For example, in the popular scenes originally developed by Richland, Morrison, and Holyoak (2006) distractor was the visually identical object (shown in a different position or orientation) that played an important role in the source scene but played no active role in the target scene (e.g., a cat chasing a mouse vs. a cat sitting when a woman is chasing a girl). We believe that distractors involved within a relation are much more difficult to ignore and may be better suited for healthy adult participants. The set of scene problems was validated in the above-mentioned pilot study (N=61). One item which yielded very low accuracy and poor internal consistency was replaced. Fig. 2 presents an example of a scene analogy with cross-mapping.

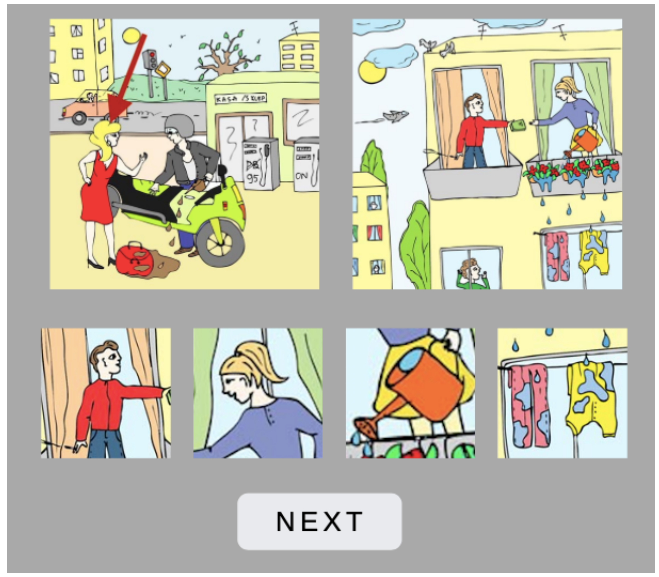

Figure 2: A sample item of the Scene Analogy Task with cross-mapping. On the left-hand side, we see a woman distracting a man who as a result overspills petrol. On the right-hand side, we see a woman distracted by a neighbor while watering her flowers and spilling the liquid as a result. The four response options presented below the scenes included the correct response (*a boy*), a distractor (*a woman*), and two irrelevant (i.e., non-distractor) objects (*a watering can* and *hung laundry*).

Geometric Analogy Task

This task consisted of 18 items in the form 'A is to B as C is to X?' where A, B, and C were relatively simple shape patterns. A and B were related according to transformations of perceptual features (e.g., shape's size, color, orientation). Participants were asked to identify one pattern out of four that was related to pattern C, as B was related to A. Fig. 3a presents an item from the Geometric Analogy Task.

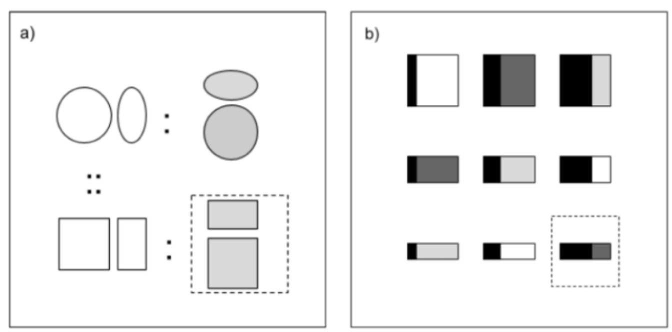

Figure 3: a) An exemplary item of the Geometric Analogy Task and b) a RAPM-like item; the correct response (dashed rim) is missing and has to be selected out of four options in the case of the Geometric Analogy Task, and out of eight in the case of RAPM matrices (not depicted in the example).

Raven's Advanced Progressive Matrices

This task consisted of 18 items out of 36 items of the original test. Each problem comprised a 3x3 matrix of shape patterns with a missing bottom-right pattern. The task was to determine the rules that govern the matrix (e.g., pair-wise progression, permutation, logical OR/AND), and apply them to identify the missing pattern out of eight response options. Fig. 3b presents an example of a RAPM-like item.

Procedure

Pictorial Analogy Task and Scene Analogy Task were computerized. Participants had 30 seconds to provide a response in each trial. The time limit was set on the basis of the pilot study and did not affect the solution rate, as compared to the pilot results. The order of trials was random for each participant. Each task was preceded by a written instruction as well as two training problems with feedback. Geometric Analogy Task and RAPM were administered in a paper-and-pencil form. Participants had 15 and 20 minutes, respectively, to solve 18 items in each test. Both tests have typical progressive item order (from easy to difficult). Between the computerized analogies and the two paper-and-pencil tests, a battery of other cognitive tasks was administered as a part of another research project unrelated to the current study. Fig. 3 presents an item from the Geometric Analogy Task and a RAPM-like item.

Results

Patterns of errors

Dependent variables in the Pictorial Analogy Task were accuracy and error rate for each distractor type. Accuracy was defined as the proportion of the number of correct responses in all 40 trials in the task. The error rate for each distractor type was computed as the proportion of the number of error choices of each type to all errors committed in the task (in total 1330 errors were committed, including 28 trials in which no response was given, the latter were disregarded resulting in the total number of errors of 1302). Accuracy in the Pictorial Analogy Task equaled M = 86.8% (SD = 11.99%, range 35% – 100%). Out of 251 participants, only 8 participants committed no error, and 218 choose distractors in at least two items. Fig. 4 presents the rates for each error option.

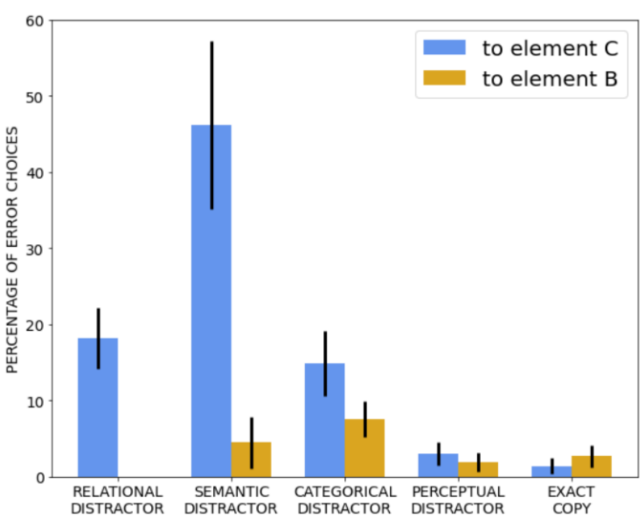

Figure 4: Percentage of error choices in the Pictorial Analogy Task computed as the proportion of the number of choices of each error option in the number of all errors committed. Bars indicate 95% confidence intervals.

Overall, distractors to B (perceptual, semantic, categorical), exact copies, and perceptual distractors to C were selected very rarely, making from 1% to 8% of errors committed, depending on the distractor type (21% of errors in total, less than 1% of all trials). Thus, these options were not the actual sources of distraction and were not analyzed further. Semantic, relational, and categorical distractors to C comprised, respectively, 46%, 18%, 15% of all errors committed (i.e., 79% of errors in total). A Wilcoxon Signed-Ranks test indicated that semantic distractors to C were selected significantly more frequently than relational distractors, Z = 8.37, p < .001, and categorical distractors, Z = 9.63, p < .001. Relational distractors were chosen slightly more often than categorical distractors, Z = 2.14, p = .032.

Accuracy in the Scene Analogy Task equaled M = 69.8% (SD = 17.15%, range 14% – 97%). Accuracy in items with cross-mapping equaled M = 59.4% (SD = 20.01%), without cross-mapping it equaled M = 80.2% (SD = 17.38%), the difference was significant, $t(250)$ = 21.51, p < .001. Majority of errors committed in the latter condition consisted of selecting the distractor option (71% of all errors).

Accuracy in the Geometric Analogy Task equaled M = 65.7% (SD = 18.11%, range 11% – 100%). Accuracy in RAPM was M = 61.1% (SD = 17.1, range 0% – 89%).

Correlations

Accuracy in the two semantically-rich tasks correlated strongly, r = .605, 95% CI [.521, .678], p < .001. There was no significant difference in the Scene Analogy Task (Cronbach's α = .83) correlation with the Pictorial Analogy Task (α = .84) between the items with and without cross-mapping. The Geometric Analogy Task correlated with the Pictorial Analogy Task at r = .547 [.454, .628], p < .001, and with the Scene Analogy Task at r = .457 [.354, .549], p < .001. Respective correlations of semantically-rich tasks with the Geometric Analogy Task (α = .72) were comparably strong, r = .547 and r = .457, Δr = .090, z = 1.92, p = .055.

Scores in RAPM (α = .78) correlated significantly with all the three analogical reasoning tasks, r = .595 [.509, .669], p < .001, for the Pictorial Analogy Task, r = .552 [.460, .632], p < .001, for the Scene Analogy Task, and r = .692 [.622, .751], p < .001, for the Geometric Analogy Task. The correlation between RAPM and the Geometric Analogy Task was significantly stronger as compared to the RAPM correlation with the Pictorial Analogy Task, Δr = .097, z = 2.3, p = .021, and the Scene Analogy Task, Δr = .140, z = 3.0, p = .003. The two latter tasks correlated with RAPM comparably strongly.

Correlations between all the three tasks that involved analogical reasoning were controlled for RAPM in order to investigate whether observed correlations could be entirely explained by general reasoning ability, or perhaps the mechanism underlying reasoning by analogy is more specific. The correlation between the Geometric Analogy Task and the Scene Analogy Task was no longer significant after accounting for RAPM, r = .123, p = .051. The analogous correlation for the Pictorial Analogy Task significantly decreased after controlling RAPM, Δr = .314, p < .001, but was still significant, r = .233, p < .001. The correlation between the two semantically rich tasks also significantly decreased after RAPM was partialled out, Δr = .192, p = .012, but remained significant, r = .413, p < .001.

Discussion

The study comprehensively examined reasoning by analogy by applying three leading paradigms: semantically-rich scene analogies and pictorial four-term analogies, as well as geometric analogies devoid of any semantic load. Also, RAPM was applied to investigate the relationship between these three tasks and fluid intelligence.

Firstly, important findings were made about distraction sources in pictorial four-term analogies. Distractors related to B were easy to ignore and did not affect the process of solving analogies, while distractors related to C did attract the reasoner's attention. This result suggests that C comprises the most important object of reference during reasoning by analogy in the A:B::C:D problems. Presumably, the course of solving four-term analogies starts with a focus on A and B to abstract a relation between these two. At this stage, no attention is given to the response choices. Then, the relation is applied to C and the given alternatives, making the reasoner especially vulnerable to C-related distractors but not B-related distractors, since object B is no longer considered at this stage. The precise definition of four distraction types (perceptual, semantic, categorical, and relational), and the analysis of error rates for each type, lead us to a conclusion that semantic association is the most important source of distraction in solving analogies. Newly defined categorical and relational distractors turned out to be also important but were chosen less frequently than semantic distractors. A relatively high error rate for relational distractor suggests that the process of response selection can be disturbed at the late stage of solving analogy after the relation has already been determined.

It is important to emphasize that the above conclusions concern young, healthy adults. In the case of children and clinical groups, it is likely that the pattern of errors would differ. Moreover, it would be interesting to apply such an extended version of pictorial analogies together with eye-tracking in order to investigate whether behavioral data in terms of error rates overlap with the amount of attention devoted to each response option, as captured by more sophisticated eye-tracking indices.

Secondly, the correlational analysis showed significant intercorrelations between the three analogy tasks. The semantically-rich tasks correlated comparably with RAPM, while the Geometric Analogy Task correlated more strongly with RAPM than with the former tasks, which is not surprising taking into account the fact that geometric analogies are often applied as a measure of fluid intelligence (see Mackintosh, 1998). In both RAPM and geometric analogies, abstract reasoning ability plays a crucial role.

Partial correlation analysis provided some insights into the role of abstract reasoning ability. The correlation between the two semantically-rich tasks and the Geometric Analogy Task significantly weakened after the RAPM score was controlled for, meaning that intelligence was responsible for some portion of the shared variance. However, the correlation between the Scene Analogy Task and the Pictorial Analogy Task remained significant after controlling for RAPM. This suggests that these two tasks shared a common mechanism, presumably related to semantic processing, which could not be explained away by fluid intelligence.

Concluding, this study comprehensively investigated the relationships between three popular analogical reasoning paradigms. It provided important insights regarding varied sources of distraction in the popular four-term analogy paradigm, pointing at the role of semantic, categorial, and relational distractors. Semantic distractors strongly affected performance also in scene analogies. The study suggests that performance in all three analogy tasks strongly relies on abstract reasoning ability, as reflected by the fluid intelligence test scores. The study also indicated that the two semantically rich analogical tasks rely on some specific mechanism, related to semantic processing, which cannot be explained by fluid intelligence.

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