Analogies May Not be as Cognitively Demanding as Previously Assumed: Evidence from a Dual-Task Paradigm with Gradually Increasing Cognitive Load

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Abstract

Making analogies is considered to depend on executive functions. We examined the role of the central executive in solving pictorial cross-mapping problems while generating random digits ranging 1-3 for one group of subjects, and 1-9 for another. We used three indices assessing different aspects of randomness and a self-report measure to evaluate the effect of the concurrent task. Subjects who had to generate digits between 1 and 9 perceived the task to be harder but still produced more random sequences than those in the smaller-range condition. Although the manipulation of cognitive load was successful, no difference was observed in the proportion of relational responses to the cross-mapping task, suggesting that analogies may not be as cognitively demanding as otherwise assumed. We also provide correlational support for the influence of individual differences in fluid intelligence on relational mapping abilities.

Keywords: analogy; working memory; central executive; relational mindset; cognitive load

Introduction

Analogies are used across various domains and to achieve different reasoning goals — to solve problems, to win arguments, to improve understanding. It seems that analogy underlies fundamental cognitive processes, such as perception, memory, categorisation and decision making — making it the core of human cognition (Gentner, Holyoak, & Kokinov, 2001).

They were defined as a process of transferring knowledge we have about one entity (source analog) onto another entity we are not familiar with (target analog) in order to better understand and remember it. This transfer is made on the basis of structural overlapping between the two entities, and not based on attributional similarities (Gentner, 1983).

Explicit and Implicit Analogies

There is a debate in the field on whether analogies are always conscious and taxing on attentional resources, or they can be automatic, unintentional and even unconscious. Researchers on one side of the debate (Cho, Holyoak, & Cannon, 2007; Holyoak, 2012; Waltz et al., 2000) emphasise arguments such as the involvement in analogy-making of areas of the prefrontal cortex and working memory resources. The role of the PFC is critical for holding, manipulating and integrating multiple relations and role bindings (Waltz et al., 1999). It also plays an essential part in inhibiting distractors during relational reasoning (Krawczyk et al., 2008). Moreover, Waltz, Laun, Grewal, and Holyoak (2000) demonstrated that solving analogical problems under dual-task conditions in which working memory was loaded by a random-digit generation task (relying heavily on the central executive component of working memory), diminished the proportion of relation-based solutions and increased the proportion of attribution-based ones. The same tendency was found by Tohill and Holyak (2000) when inducing state anxiety in participants. According to Attentional Control Theory (Eysenck, Derakshan, Santos, & Calvo, 2007), this detrimental effect is due to anxiety decreasing attentional control and increasing attention to threat-related stimuli which naturally occupy working memory. However, Hristova and Kokinov (2011) obtained different results indicating that heightened anxiety leads to superior encoding of relations which, depending on the complexity of the mapping task, may improve performance (Hristova, Petkova, & Kokinov, 2013).

Based on the accumulated evidence about the reliance of analogical reasoning on executive function resources, Holyoak (2012) argues that analogy-making is an explicit, effortful process that depends heavily on working memory and other executive functions. He concludes that any unintentional analogical transfer is based merely on relational priming. Nevertheless, Hristova (2017) maintains that the empirical research behind these arguments is mostly based on explicit instructions to make, find or verify analogies.

On the other side of the debate (Hristova, 2017), evidence is taken into account such as instances of analogical transfer with no explicit instruction, no awareness and even when this may hinder task completion. Also, in some of these cases, relational priming was controlled for and did not predict the results (Day & Gentner, 2007; Hristova, 2009a, b, as cited by Hristova, 2017). It can thus be deduced that it is not relational priming that stands behind these transfers of knowledge and analogical mapping can indeed be both explicit and implicit, effortful and effortless, intended and unintentional. Furthermore, Speed (2010, as cited by Hristova, 2017) claimed that automatic analogies might be processed by the same PFC regions as the explicit ones but since they would involve less activation, they might not be as easily detectable by neuroimaging techniques.

Rationale of the Current Study

Our goal was to explore the role of the central executive component of working memory in analogy-making. A task that reflects its capabilities is random generation of items (Baddeley, Emslie, Kolodny, & Duncan, 1998). Random number generation is used in dual-task research paradigms to investigate the role of the central executive in different cognitive processes (e.g. syllogistic reasoning (Gilhooly, Logie, Wetherick, & Wynn, 1993). Waltz et al. (2000) reported an experiment (Experiment 2) in which they used the random number generation (RNG) task with 9 alternatives (digits 1 to 9) to demonstrate the important role of the central executive in solving analogical problems. They compared it with that of the phonological loop component of WM and found no difference in the level of depletion of the ability to perform relational mapping between the two conditions, as compared to the performance of a control group that did not perform a second task.

In this study, we wanted to examine the particular role of the central executive component more closely through a comparison between two active groups. Difficulty of the RNG task depends on two independent factors (Towse, 1998): digit range (the broader the range, the harder the task) and interval length (the shorter the interval between generation of two consecutive digits, the harder the task). We kept the interval the same for the two groups and varied only the range: 1-9 for the high-load group, and 1-3 for the low-load group. Towse (1998) found that an important effect of increasing set range makes representing candidate responses more difficult: having more digits to select from makes it harder to choose a suitable alternative to continue the sequence, which leads to particular digits and two-digit combinations being chosen too often. It was important to be able to clearly differentiate between the two groups, so we obtained subjective measures of perceived difficulty and objectively scored participants' performance on the task using three indices measuring redundancy, randomness and adjacency (Towse, 1998).

We expected participants would subjectively report different levels of perceived difficulty of the task and the group with a bigger set size would perform worse as reflected by randomness, redundancy and adjacency indices.

The main hypothesis of the study was that (assuming our manipulation of the level of working memory depletion was successful), there would be a significant difference in the number of relational responses given to the analogical problem between the two groups reflecting analogy-making dependence on working memory resources.

Last but not least, we added a measure of fluid intelligence — an abridged excerpt of Raven's Progressive Matrices (Raven, Raven, & Court, 2003). Individual differences in RPM performance (i.e. in fluid intelligence) have been found to correlate with ability to make relation-based mappings. Bliznashki and Kokinov (2010) reported in an experiment a weak-to-moderate positive correlation (r_{pbis} = .36) between the proportion of correctly solved RPM trials and probability of providing a relational response to the target task. Vendetti, Wu, and Holyoak (2014) similarly report a moderate ($r(26)$ = .41) positive correlation. Kubricht, Lu, and Holyoak (2017) found that fluid intelligence influences relational transfer by aiding in comprehension of the source analog.

We used the E series of Raven's Progressive Matrices which was chosen based on findings that solving RPM problems which apply rule sets (Distribution of 3, Distribution of 2, Addition, and Subtraction) that require analytic reasoning is associated with activation of PFC areas that are also linked with relational processing (Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997). Successful solution of these problems involves executive control processes that are required to analyze complex problems, derive a set of relations between elements, develop solution strategies, and monitor and adapt performance as problems become more complex (Wiley, Jarosz, Cushen, & Colflesh, 2011).

Method

Participants

A total of 59 participants took part in the experiment (19 male, 40 female). Their mean age was 23.1 (SD = 4.92; range: 18–40). All of them were volunteers and received course credit. All were informed about the procedure of the experiment and signed an informed consent form.

Stimuli

We used the 12 items of the E series of Raven's Progressive Matrices as a measure of fluid intelligence, as well as items C9, D3 and D8 for training. For the analogy task 15 grayscale cross-mapping picture pairs were used (see Figure 1). The pictures were the ones used by Hristova et al. (2013), where some of the stimuli were redrawn versions of the ones used by Markman and Gentner (1993) and Tohill and Holyoak (2000) with preserved relations between the objects, while the others were added by the authors (Hristova et al., 2013). Fifteen more pictures that did not contain cross-mapping (but were otherwise similar to the one shown in Figure 1) were used for the training sessions.

The experiment was conducted on a 13-inch MacBook Pro laptop (Apple, CA, 2015). Stimuli were presented and data were collected using a desktop application custom-made specifically for this experiment.

Design

The study applied a between-subjects design with one independent variable: working memory (WM) load level (high vs. low). The difference between the two groups was defined by the variation of the concurrent task they were performing while solving analogical problems: generating random digits ranging either 1-3 for the low-load group, or 1-9 for the high-load group. The dependent variable was proportion of relational responses given to the analogy problems. Participants were randomly assigned to groups.

Procedure

Participants were tested individually with an experimenter in an experimental cubicle. They gave consent after being informed about the procedures of the study and that it had to do with thinking and digit generation. The duration varied between participants but was generally about 20 minutes.

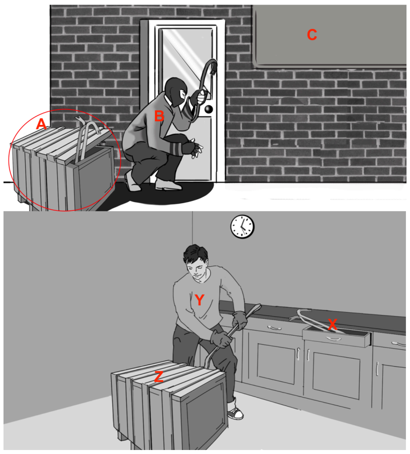

Figure 1: Example of a picture-pair used in the analogy task. Participants had to indicate which object in the lower picture corresponded to the highlighted object in the upper picture. The relational solution for this pair is X (a place for storing instruments), and the attributional one is Z.

The experiment began with three training sessions: analogy alone, random number generation alone, and combined (analogy task along with RNG).

The pictorial analogy tasks comprised of two pictures one below the other with three-four distinct objects each. Participants were asked to indicate 'which of the objects in the picture below corresponded to the highlighted object from the picture above'. The training set of picture-pairs was different from the one used in the actual experiment both in terms of objects and relations. Also, there were no cross-mapped objects in the training picture-pair set. Five picture-pairs were used in the analogy alone and ten in the combined training task. No feedback was provided.

The aim of the RNG-only training session was for participants to get used to the procedure of saying out loud a digit (between 1-3 or 1-9, respectively for the two groups) each time they heard a tone. The intervals between the tones decreased from 2,5 s, through 2 s, to 1,5 s (each interval was used for 40 s which resulted in a 120 s duration of the RNG training). At the end of this session participants were asked to rate how difficult they thought the task was on a scale from 1 (very easy) to 7 (very difficult).

The final training session was a combination of the two tasks — participants had to solve ten pictorial analogies while simultaneously generating random digits at a 1,5 s interval. At the end of this session, too, participants were asked to rate how difficult the task was on a scale from 1 (very easy) to 7 (very difficult).

Participants completed the training tasks in their own pace. No additional time was left in-between sessions.

After the training participants solved the 12 items from the E series of RPM (presented in their usual order). The original instructions were provided and participants were told they had one minute to solve each item (although the time limit was in fact 3,5 minutes). For the three training items they received feedback of whether their answer was correct, and if not — the correct answer was highlighted.

The experimental task included simultaneous solving of the 15 cross-mapping pictorial analogy problems and RNG with a 1,5 s interval. The instruction was purposefully ambiguous — participants were told to indicate which object corresponded to the highlighted one without specifying whether to do so on a relational, or on a featural basis. Presentation of every stimulus was preceded by a 100-ms fixation cross and the presentation of the pictorial analogy stimuli was randomized across participants. A computer mouse was used to indicate answers and the RNG sessions were recorded. All procedures were approved by the Ethics Committee of New Bulgarian University, Department of Cognitive Science and Psychology.

Statistical Analyses of Data

The performance on the RNG task was assessed with three indices which measure different aspects of it (Towse, 1998).

The first one, RNG, is an index of randomness which measures the distribution of all immediate response pairs and rises the more frequently one and the same pairs are produced (e.g. 1 followed by 2, or 9 followed by 6, repeatedly). Low scores indicate equal use of all possible pairs. The formula for calculating RNG is the following:

$$RNG = \sum f_{ij} \log f_{ij} \,/\, \sum f_i \log f_i$$

where f_{ij} is the frequency of each possible pair of responses; f_i is the frequency of the ith alternative.

The next index, R, measures redundancy and as some alternatives are generated more or less often than others, R increases. The formula for R is the following:

$$R = 100 \times (1 - [\log_2 n - (\sum (n_i \log_2 n_i)/n] / \log_2 m))$$

where n is the number of digits generated, n_i is the frequency of the ith alternative, and m is the number of response alternatives.

The third index is A which equals the percentage of pairs made up of adjacent digits on the number line (i.e. '1,2' or '2,3' or '3,4'). The formula is:

$$A = (\text{number of adjacent pairs} / \text{number of response pairs}) \times 100$$

Using these indices to compare sequences between groups requires standardization because the scores are affected by different set sizes. We calculated non-randomness as $(O - E)^2/E$, where O is the observed value of the index at hand, and E — the expected value for a random sequence. We derived the expected values of the scores from a computer generator producing 1000 strings of digits for each set size. The strings were of the same length as the mean length of strings produced by participants in each condition. After this standardization process scores show how much participants' strings deviated from an appropriate random sequence (Towse, 1998). Thus, higher scores reflect less random performance for each index.

Results

Preliminary Data Analyses

The data were trimmed based on response time: 37 out of 885 cases were trimmed from the set of analogy-task responses because they deviated by more than two SDs above the mean RT, and 30 out of 708 — from the set of RPM responses following the same procedure.

Random Number Generation Task

All three indices (RNG, R and A) differed significantly between groups, although not in the direction we anticipated. The low-load group (set size: 1-3) performed less randomly as measured by RNG ($t(57) = 8.18$, $p < .001$, $d = 2.11$), produced more redundant sequences as measured by R ($t(57) = 55.14$, $p < .001$, $d = 14.47$), and used adjacent digit pairs more often as measured by A ($t(57) = 14.83$, $p < .001$, $d = 3.83$; see Table 1 for descriptives).

The subjective ratings of task difficulty showed that participants found the task to be significantly more difficult with 9 alternatives than with 3 alternatives, both when they had to generate digits only ($t(57) = 2.38$, $p = .021$, $d = 0.61$), and when they had to generate them while solving an analogy task ($t(57) = 2.8$, $p = .007$, $d = 0.72$; see Table 2 for descriptives).

Table 1: Descriptive statistics for RNG, R and A scores

	Group	Mean	95% CI of Mean	SD
RNG	low load	1.11	0.84, 1.38	0.72
	high load	0.03	0.01, 0.05	0.05
R	low load	96.18	95.51, 96.85	1.77
	high load	5.99	2.77, 9.21	8.63
A	low load	570.64	494.11, 647.17	201.22
	high load	21.46	11.82, 31.1	25.82

Table 2: Descriptive statistics for subjective measures of task difficulty (on a 7-point Likert scale where 1 = very easy and 7 = very difficult)

	Group	Mean	95% CI of Mean	SD
RNG only	low load	2.59	2.06, 3.12	1.40
	high load	3.43	2.93, 3.93	1.33
RNG and analogies	low load	4.66	4.16, 5.16	1.32
	high load	5.60	5.12, 6.08	1.28

Analogy Task

No significant difference was found in the proportion of relational answers (see Figure 2) between the high-load (M = 0.57; SD = 0.31) and the low-load group (M = 0.61; SD = 0.29; $t(57) = 0.51$; $p = .61$), nor in the proportion of attributional answers (M = 0.35, SD = 0.29 for high-load group; M = 0.34, SD = 0.28 for low-load group; $t(57) = 0.22$, $p = .83$).

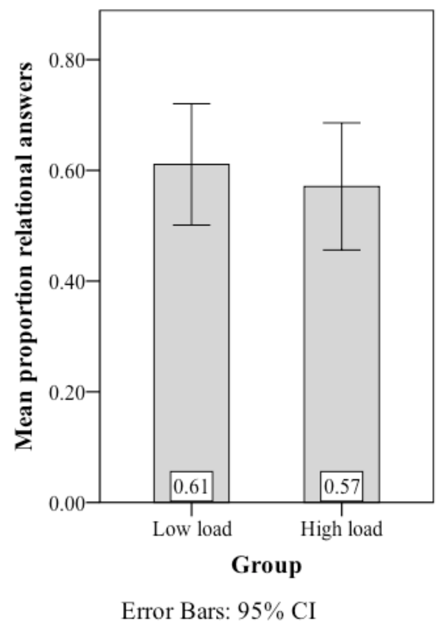

Figure 2: Mean proportion relational answers to the analogical problems by the low and the high load groups. Difference is not statistically significant.

RPM Task

There was a weak-to-moderate positive correlation between RPM scores and proportion of relational answers (Spearman's *rho*(59) = 0.359, $p = .005$, see Figure 3), and a weak negative correlation between RPM scores and proportion of attributional answers (Spearman's *rho*(59) = -0.287, $p = .027$, see Figure 4). In other words, obtaining a higher score on the RPM problems meant providing more relational responses to the pictorial cross-mapping task, and respectively, a lower RPM score was related to a higher probability of providing feature-based solutions to the analogical task. Correlations reported in the literature were of similar magnitude (see Introduction).

Discussion

In this experiment, after inducing a relational mind-set, we varied the extent of concurrent cognitive load imposed on two groups of participants by using a dual-task paradigm, and obtained no difference in their performance on a cross-mapping pictorial analogy task. This finding is not in line with previous studies investigating the link between analogy-making and the executive component of working memory (Waltz et al., 2000).

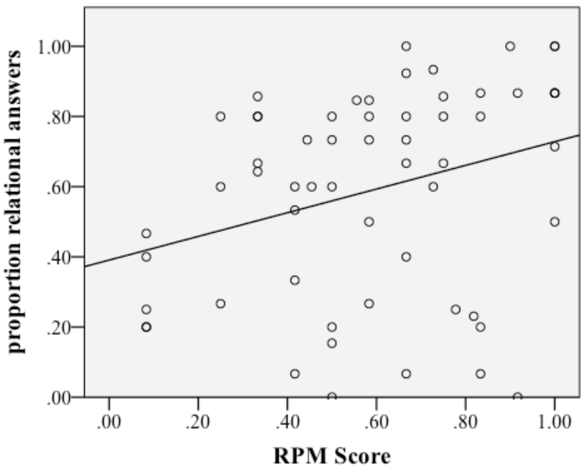

Figure 3: Correlation between proportion of relational responses given to the pictorial cross-mapping task and Raven's score (presented here as proportion correct out of 12). Spearman's *rho*(59) = 0.359, *p* = .005.

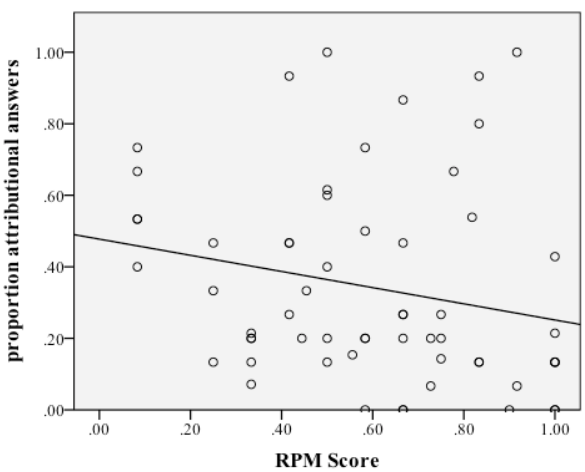

Figure 4: Correlation between proportion of attributional responses given to the pictorial cross-mapping task and Raven's score (presented here as proportion correct out of 12). Spearman's *rho*(59) = -0.287, *p* = .027.

The correlations between Raven's performance and proportion of successful relational mappings that we obtained were similar to previous findings (Bliznashki & Kokinov, 2010; Vendetti, Wu, & Holyoak, 2014) which supports the possibility that individual differences in fluid intelligence may inform individual differences in ability and tendency to pay attention to and comprehend relations in an analog (Kubricht, Lu, & Holyoak, 2017). This also endorses the notion that common executive resources are used for the two types of tasks.

As for the manipulation of cognitive load level, different measures of random number generation performance yielded conflicting results. On one hand, the three indices used to measure performance objectively showed that the low-load group's sequences deviated from randomness more so than those of the high-load group. On the other hand, participants subjectively found the task to be more difficult when the digit range was 1-9 than when it was 1-3, both for the generation task on its own and when coupled with analogy making. If we adopt the zero-correlation criterion proposed by Dienes, Altmann, Kwan and Goode (1995) for testing conscious and unconscious processing, and sensitivity of objective and subjective measures of self-awareness (where positive correlation between confidence and accuracy measures implies the use of conscious knowledge in assessing one's own performance), we may speculate that the discrepancy between our two types of measures is due to lack of explicit knowledge when providing a self-assessment of performance. This lack of agreement between objective and subjective assessment of task difficulty may be a result of people's variable conceptions of what randomness is, depending on the interpretation of the task at hand (Nickerson, 2002).

Even though the results are inconclusive with respect to the exact way RNG affects working memory resources, both measures differentiate between the two groups. So, based on observations about the dependence of analogy-making on executive resources, it is expected that there should be a difference in the proportion of relation-based mappings between the two groups.

However, we found no differences in the concurrent analogical task — neither in the proportion of relational responses, nor in that of attributional ones. These results challenge the view that analogy-making is a strictly effortful process that relies heavily on working memory resources. Moreover, the fact that neither the relational, nor the attributional choices differed reliably across conditions, indicates that the same mode of thinking was used in both conditions.

It is important to note that these results were obtained in a context of a manipulating the level of cognitive load, and not merely based on a comparison between an active and an inactive group. Even though we only had two levels of cognitive load, the results can still be considered informative as far as mechanisms involved in the processes are concerned. Naturally, if a group of participants performing a single task was compared to a group performing two tasks simultaneously, their performance would differ but this is not necessarily indicative of the nature of the cognitive processes involved. It may just be an effect of the experimental paradigm used. By contrast, manipulating the extent of cognitive load puts different groups in more comparable settings that may yield more trustworthy results, as long as the manipulation is successful.

The scope of the current study is limited. More conditions need to be explored with regards to the resources needed for relational mapping in order to be able to draw stronger conclusions about its nature as an effortful and/or effortless process. That is why our future agenda includes exploring several more conditions, including control groups with no concurrent task, so that we may have a good baseline.

Conclusion

With this study we introduce arguments favoring the possibility that successful analogical mapping may not depend heavily on working memory resources and is possible regardless of their depletion. We emphasise the importance of applying a research paradigm which varies cognitive load gradually when the goal is to examine the extent to which cognitive processes depend on a limited-resource component, such as the central executive, as well as to determine the mechanisms of its involvement.

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