Executive Control in Analogical Mapping: Two Facets

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Abstract

In recent studies, analogy-making has been shown to depend on the ability to resist interference within working memory (WM). Less evidence refers to the other facets of executive control (EC), especially to the goal-directed selection of relational information. In this study, the load on two above mentioned EC functions and on WM capacity was manipulated in a single picture mapping task. Next to replicating the previous findings on the importance of dealing with distracter interference within WM, the current results demonstrate that the efficiency of relational mapping also depends on the goal-directed search for WM input, and that these two EC functions may be dissociable in mapping. Moreover, it was found that the impact of distraction can be linked to whether relations, in which distracters occur, have not exceeded WM capacity.

Introduction

Analogical reasoning is a flagship example of the human ability to flexibly form and manipulate explicit representations of structure (Hummel & Holyoak, 2003). Making an analogy requires identifying systematic relational correspondences between two analogs (e.g., situations), irrespective of superficial similarities (if they conflict with relational ones) or differences (especially, if they are huge) between them (e.g., Gentner, 1983). This structure-mapping process allows one to infer new goal-relevant information about one analog (*target*) from the second analog (*source*). Thus, analogy is an important tool for dealing with novelty and one of the major vehicles of human intelligence (e.g., Holyoak, 2005).

The inherent computational challenges of processing relational representations (Doumas & Hummel, 2005), and the fact that variance in the efficiency of analogical reasoning is only partially explicable by knowledge accretion (e.g., Doumas, Morrison & Richland, 2009), has made many researchers and theorists postulate that the emergence of analogy is underlain by the efficiency of some constitutional cognitive capacities (or parameters). Of these, working memory (WM) was considered to be the most important (see Morrison, 2005 for review). Yet, explaining analogy-making by WM constraints seems to be quite intricate.

More than WM Capacity

WM is a capacity-limited system responsible for active maintenance, rapid access and easy updating of goal-relevant information (Cowan, 2005). If WM is overloaded by a parallel task (Waltz, Lau, Grewal & Holyoak, 2000), impaired by brain damage (Waltz et al., 1999), or if the number of variables interacting in relational representation grows (Halford, Baker, McCredden, & Bain, 2005), relational reasoning becomes less efficient. According to relational complexity theory, the load of relational representation on WM increases exponentially with the number of interacting variables that must be concurrently manipulated (i.e., relationally integrated). Human WM is probably typically limited to the parallel processing of up to one quaternary relation, that is a relational representation with four variables (Halford, Wilson & Phillips, 1998).

However, when reflecting on the limited nature of WM capacity, it is important to understand internal cognitive constraints on the proper selection of WM input, by means of which humans single-handedly, but with various degrees of success (e.g., Chuderska & Chuderski, 2009), abstract structural similarity between analogs from other structural and (sometimes very compelling) semantic information. It seems plausible that relational integration might be influenced by the efficiency of earlier goal-driven attentional selection (see Awh, Vogel & Oh, 2006 for a discussion of attention as the "gatekeeper" for WM), or by the efficiency of managing subsequent reasoning steps (e.g., Carpenter, Just & Shell, 1990), which are necessarily isolated out for reduction of complexity (Halford et al., 1998).

On the other hand, the content of variables integrated in WM may perceptually or semantically conflict with the structural information they convey (e.g., Markman and Gentner, 1993). Since processing many distracters leads to no success, the need to deal with distraction within WM, while analogizing, seems indispensible (e.g., Viskontas, Morisson, Holyoak, Hummel, & Knowlton, 2004).

The potential causes for processing irrelevant information by WM, or doing it inefficiently, are delineated in LISA – an artificial neural network model of relational reasoning (Hummel & Holyoak, 2003). LISA dynamically binds roles (i.e., variables) and fillers (i.e., their content) into relations by the synchrony of firing their distributed semantic (featural) and localist (structural) representations. The model contains an intrinsic capacity limit, since only a confined number of such role-filler bindings can oscillate cleanly asynchronously in one processing cycle. The weaker the inhibitory competition between active units, the less role-filler bindings are cleanly discriminated. The strength of inhibitory competition between propositions in problem representation also determines which of them will enter WM and in what order; this is critical for mapping performance (Kubose, Holyoak & Hummel, 2002). The weaker the inhibition, the less reliance LISA has on the importance assigned to propositions, and the less accurate will be its eventual mapping.

Thus, an important source of cognitive constraints in relational reasoning might come from the effectiveness of executive control. Executive control (EC) can be defined as a set of cognitive processes that, instead of representing mental states directly, influence and organize such states in the context of some internal goal. Recent theories assume that EC is an emergent process arising from the dynamic interaction of several independent, elementary control mechanisms (Braver, Gray, & Burgess, 2007; Engle & Kane, 2004). There is some evidence that these functions significantly correlate with abstract reasoning (see Chuderski & Nęcka, 2010, for a review).

Executive Control in Analogical Reasoning

The fact that the maintenance and proper application of a reasoning goal is critical for analogical reasoning might be inferred from findings which show that the frequency of recognizing relational similarity is higher when multiple, instead of single, objects are to be mapped across analogs (Markman and Gentner, 1993; Waltz et al., 2000). Such a manipulation might make the goal of relational processing more salient to participants and aid (or substitute) selection of what should enter WM for structural alignment. It could also be hypothesized that the overriding initial mappings, if they turn out to be incorrect (Keane, 1997), might call not only for inhibition, as proposed in LISA, but also for some goal management mechanisms. More directly, it was shown that mapping performance correlates with most of the proposed executive functions, with three of them (WM updating, switching, and dual-tasking) being accounted for through the monitoring and application of goal and through response inhibition (Chuderska & Chuderski, 2009).

Another function of control within analogical reasoning relates to resolving conflicts and coping with (distracter) interference. For example, Gray, Chabris, and Braver (2003) observed that brain activity in neural structures, recruited by a high-interference condition of a WM updating task, correlated with relational reasoning performance. Some evidence for links between abstract reasoning tests and response inhibition and interference resolution was reviewed by Dempster and Corkill (1999). If superficially similar objects are placed in different relational roles (i.e., are cross-mapped) in structures that are to be mapped, effective interference resolution seems necessary to overcome the observed relational mapping impediment, (e.g., Markman & Gentner, 1993). Cho, Holyoak, and Cannon (2007) manipulated the level of internal complexity and interference of a simple analogical mapping task, demonstrating that young participants' reaction times overadditively increased with relational complexity and interference. Similar decreases in performance by manipulating these two factors were observed in older adults (Viskontas et al., 2004). Richland, Morrison and Holyoak (2006) found that as children get older they are more efficient in dealing with both relational complexity and distraction, which was computationally accounted for by inhibitory competition in LISA (Morrison, Doumas and Richland, 2006).

It seems that goal-driven selection of relevant information for relational processing, as well as the inhibition of irrelevant information, constitute two sides of a "control coin" in analogical reasoning. No study to date has addressed both sides of the coin within a single task. For example, in the studies by Viskontas et al. (2004) and Cho et al. (2007) subjects were provided with all the relevant dimensions and were required to integrate them in WM while ignoring unequivocally irrelevant dimensions. In studies where similar relations were to be induced by the subjects themselves (e.g. Markman and Gentner, 1993; Waltz et al., 2000; Richland et al. 2006), no manipulation of the need for selectiveness occurred.

The goal of the presented study is to extend the empirical data on the role of EC in managing WM content in analogical reasoning with semantically meaningful material, which lacks the predetermination of a relevant relational structure. This will be done by attempting to manipulate experimentally the processing requirements for the above two mentioned aspects of EC. The load of WM capacity will also be varied. Unlike in any previous study known to the author, the needs for attentional selection, interference resolution and relational integration will all be varied in a single analogical mapping task. This procedure should allow one to explore, whether the two postulated EC faculties have dissociable or interacting effects on WM performance in analogical mapping.

The Study

The picture-mapping paradigm was used, as introduced by Markman and Gentner (1993) together with a cross-mapping procedure, advanced by Richland et al. (2006) *inter alia* by relational complexity manipulation, and applied in numerous other studies of analogical mapping (e.g., Tohill and Holyoak, 2000; Waltz et al., 2000). The task consists in analyzing the two scenes, presented to participants at once, and then deciding which object from the target scene best goes with the indicated object from the source scene. The subjects are instructed to search for a common "pattern" in the two pictures. The scenes usually depict simple causal relations, such as "towing" (see example in Fig. 1 from the current study).

The relational complexity (RC) was operationalized as the number of relational arguments (i.e., objects forming a relevant relational structure) to be processed in parallel for successful mapping. Thus, it was slightly different from the study of Richland et al. (2006), where RC was manipulated by necessarily repeating the same relation in a scene. There were either binary (involving two objects) or quaternary (four objects) relations to be mapped.

Unlike in any previous study, the total number of objects in the scene, and therefore the saliency of relevant relations, was factorially varied. It was thought of as an operationalization of the need for a goal-directed selection of structure mapping input. The relevant relations were "hidden" among five or ten objects in total. All other relations than those that were relevant ones, which could be possibly identified among the objects in a scene, were unique to only one scene. Assuming that more overt relational similarity in relatively semantically impoverished analogs constitutes a cue for engaging in relational mapping (i.e., it reminds task's goal), respective enriching the scenes (independently of relational complexity) seems to be a clear-cut way to make this cue less direct and thus more dependent on internal activation. Moreover, having to search for a relevant structure through the number of propositions, clearly exceeding WM capacity, seems to be more dependent on the quality of goal monitoring over the necessarily sequenced reasoning steps.

Since Cho et al. (2007) demonstrated that distracting information is detrimental only if attended to and actively maintained in WM, the manipulation of the need for interference was constrained to the cross-mapping procedure. That is, the presence of semantically (and to some, but never to the full, extent also featurally) similar object in different relational roles was varied always within relevant relations - like in the studies by Markman and Gentner (1993), but unlike in those by Richland et al. (2006). This objective was to ensure that the subjects' attention was not diverted from the relevant relational structure by a distracter external to it, but rather to increase the probability that distraction will affect the attempted structure mapping.

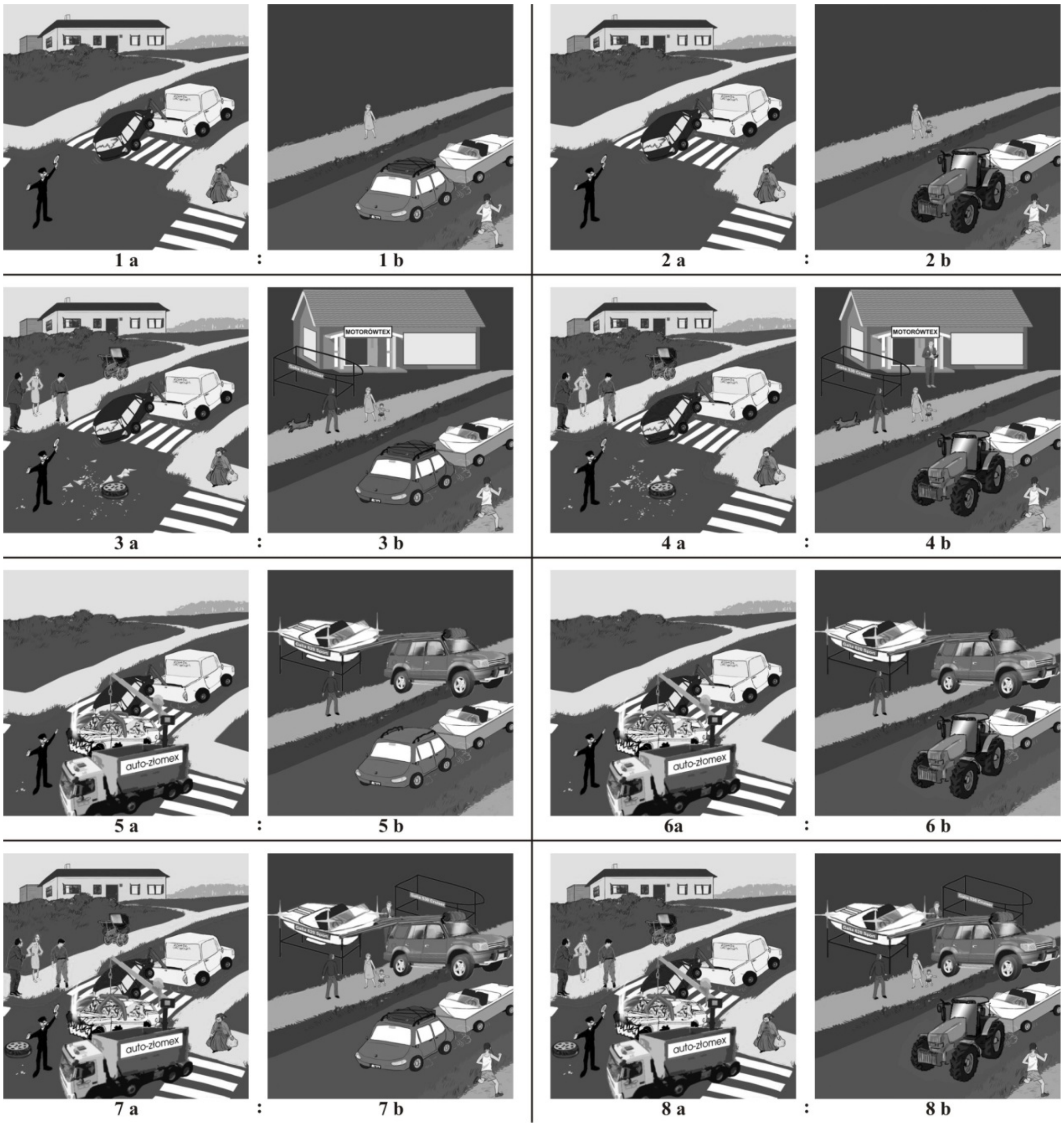

Figure 1. The example of one set of pictures of the analogical mapping task. The towed passenger car (with the *boat-wagon* object as a counterpart), and the towing lorry (pairs N^{o} 1-4) or the loading lorry (N^{o} 5-8) were highlighted for mapping. Odd numbers label pairs with a distracter (the towing passenger car in *b*s). Pairs in third and fourth rows contain quaternary relations (towing and loading are to be integrated). First and third row present high-saliency pairs.

It was expected that all three above manipulations will decrease the subjects' ability for relational mapping, but that their impact would be differential due to tapping into qualitatively distinct, although highly intertwined, cognitive capabilities. Viskontas et al. (2004) and Cho et al. (2007), from their results obtained in a similar, relatively simple mapping task, argued that the overadditive effects of RC and distraction suggest that relational integration and inhibition depend on the common pool of WM resources. However, some researchers suggest there is no reason for EC to operate more or less strongly in different WM load conditions (e.g., Embretson, 1995; Unsworth and Engle, 2005). Also, in the scene-mapping study on children by Richland et al. (2006) RC x distraction interaction occurred only in a group of 3-4 year olds. Thus, it seemed worth re-examining the RC - distraction relationship in a picture mapping task of more realistic complexity and administered to adults. As to the manipulation of relevant relations' (goal's) saliency, it was hypothesized that it will result in relational mapping decrements due to the worse discriminability of relevant relations.

However, no interaction between RC and saliency was expected. Although it appears that the whole scene has to be initially placed in WM to screen out irrelevant information, the impact of the difficulty of this selection process should not be different when more or less complex relations have to be integrated in WM for structure mapping. This is because the selection of input can be done incrementally, while RC taps into the exact WM capacity limits (Halford et al., 1998). Yet, RC and need for more rigid selection should additively affect the overall mapping performance.

Also, no interaction between saliency and distraction was expected due to the assumption that they reflect two different facets of EC, which are functionally distinct although highly related faculties (Braver et al., 2003). Thus, both EC manipulations in this study were expected to have additive influence on mapping performance.

The experiment reported here was a part of a bigger study to be reported elsewhere. Each participant solved the task reported here as their first in the whole session.

Method

Participants The participants were 122 inhabitants of Częstochowa, Poland (age = 16-44 years, M = 22.15, S.D. = 3.77, 62 females) recruited by flyers, newspaper and Internet ads. Each participant was paid 50 PLN (~10 EUR) and received a CD gift for their participation.

Materials and design. The scene mapping test contained a set of fifty-six picture pairs depicting every-day instances of common relations (e.g., destroying, giving) among conventional objects (e.g. a ceiling, money). All test items were similarly colorful and detailed, and were chosen from one hundred and three pilot items according to the items' reliability. No relation or object was repeated across the test. The quaternary (or equivalent) relations were created from the binary ones by extending the critical structure by two more objects necessary to be included in successful mapping. For instance, the relation of towing one object by another was extended by the third object, which remained behind for some reason, being loaded for transport by a fourth object (Fig. 1. 5-8). The example of distraction manipulation might be the changing role of a passenger car in a towing relation (Fig. 1., odd numbers). The spatial location of the corresponding objects was carefully varied within and across the pairs so as not to cue mapping. The pictures contained either five (Fig. 1., 1,2,5 & 6) or ten (Fig. 1., 3, 4, 7 & 8) objects in total. 2 × 2 × 2 repeated-measures design, with three factors: relational complexity (bi- vs. quaternary relations), relational saliency (five vs. ten objects within a scene), and distraction (absent vs. present), resulted in eight fully balanced experimental conditions. In order to control for the difficulty of specific scenes, like in the Richland et al. (2006) study, counterbalanced versions of each scene were created to match each experimental condition. The assignment of an item's versions to a test's version, as well as of test's versions to participants, was randomized. Each participant solved 56 different scene pairs, seven per condition, and the other twelve items in the training set representative for all conditions. The items' presentation order was fully randomized.

Procedure The task was administered on laptop computers (1280 × 800 pix. display resolution) in a group of four to five participants accompanied by the experimenter. The pairs of pictures were presented horizontally, each 5×5 inches large, with the source picture always on the left. The administration software allowed for visual separation of objects to be taken into account by the participants. This was done by covering the rest of the picture, apart from a particular object, with a semi-transparent filter, when a mouse cursor was over this object. Objects sometimes were elements of bigger objects. For example, a hand was separated from "the rest" of a person in a relation where soiling a hand, was critical; or it allowed to impose consideration of a pair of people as one entity, where the relation between pairs of people was a part of the to-be-mapped structure. Two objects were to be mapped for each pair of scenes.

Each participant received the same oral, detailed self-paced written and movie instructions. Each of the subsequent training items were followed by precise feedback. The instruction was to carefully explore pairs of pictures in order to first analyze what links exist between objects within each scene, and then to search for repeated pattern of these links across two scenes. The concept of the same relational role was carefully explained to participants and they learned that they will be required to indicate objects in the same roles in the other picture. They also learned that there might be two or four objects involved in a pattern, so that they should always search for the most complex pattern. Participants were instructed to first detect objects that need to be taken into account and then to verify if they recognized them correctly. A one-word name of an object appeared in the panel right under the picture when the cursor was over this object. The time for exploration was limited to 100 s, which had been validated as sufficient in pilot study. However, participants were encouraged to press a space bar as soon as they knew what the common pattern and object correspondences were. Once the time limit was reached or the space bar pressed, the first object in the source scene was highlighted and this picture became "frozen" for further exploration. The participants were to quickly click on this object with their mouse in the target scene, if they believed it played the same role as the highlighted one. As soon as they clicked in their chosen target object, a second object in the source scene was highlighted and its best counterpart in the target scene was also to be mouse-clicked. The choice of the first object excluded it from options for the second choice. There was a five second limit for a particular object's choice. Which relational role (i.e., agent or patient) was to be first placed in correspondence was randomized; in the distraction condition, however, the distracting object was always highlighted first. One object was highlighted across all versions/ conditions, but the other object varied between RC-conditions of a scene, in the way that in quaternary relations the second highlighted object was always from the "extended" part of the structure. The participants took one refreshment break (max. seven minutes) after completing 28 test items. Together with instruction and training, the task took up to two hours, depending on participant speed and the duration of the break.

The dependent variable was correct choice for both objects counted on an all-or-none basis.

Results

All analyses were done with Statistica 8.0 software. Nondirectional null hypothesis significance tests (with α value adopted at .05) and their p values are reported.

Mean correct responses for all conditions are depicted in Table 1. Paired *t*-tests showed that performance in all conditions was above chance level, conservatively defined as .2. In the *high RC/low saliency/distraction* condition, the value of this statistic was: $t\ (121) = 4{,}83$, $p < .001$.

Table 1. Mean correct responses in all exp. conditions

Saliency	Distraction	Relational Complexity	
		Binary	Quaternary
High (5 objects)	No	.62	.50
	Yes	.40	.36
Low (10 objects)	No	.58	.40
	Yes	.32	.28

Each factor yielded a main effect, thus validating the experimental manipulation. A 2 (RC) × 2 (saliency) × 2 (distraction) MANOVA revealed that accuracy of relational mapping decreased: as RC increased (F [1, 121] = 88.14, p < .001, η^2 = .42), as saliency decreased (F [1, 121] = 50.89, p < .001, η^2 = .30), and when distraction occurred (F [1, 121] = 292.98; p < .001, η^2 = .71). The only reliable interaction was two-way RC × distraction interaction, F (1, 121) = 28.872, p < .001, η^2 = .19. Post hoc tests (Tukey's HSD) indicated that differences between all means of this interaction were reliable, p < .01. As illustrated in Figure 2., the mapping accuracy dropped when distraction occurred, but the detrimental effect of cross-mapped foil was smaller in the high relational complexity than in the low relational complexity condition.

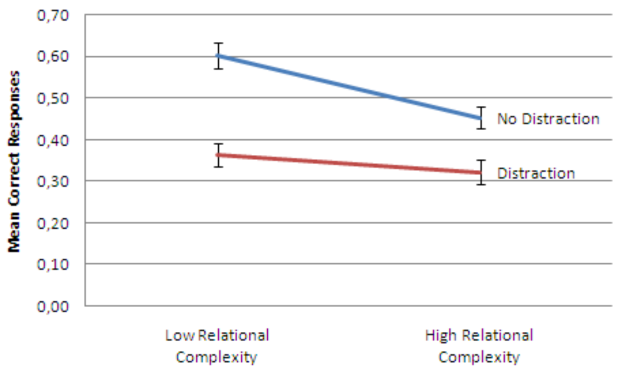

Figure 2. Interaction between Relational Complexity and Distraction. Error bars indicate standard error of the mean.

Discussion

Using a modification of Richland et al. (2006) scene mapping task the role of EC and WM as constraints on structure mapping was examined in adults. Unlike in any previous study the requirements for goal maintenance and application, for dealing with distraction and for relational integration were factorially varied in a single task.

First of all, the results replicate the previous findings in children that with increasing number of variables to be integrated and with similar objects appearing in different relational roles the level of mapping performance drops (Richland et al., 2006). Importantly, however, the presented study extends this evidence by showing that decreasing the saliency of relevant relational structure in a task also reliably impedes structure mapping. Together, these outcomes clearly exemplify the role of two EC faculties in relational mapping. Namely, EC might not only be reflected in interference resolution (Cho et al., 2007) or inhibition (Viskontas et al., 2004) within WM. It seems that EC is also involved during prior goal-directed search through structurally and semantically complex information to select WM input, as relevant for mapping.

The reason that the need for goal management and application was pronounced in this study was probably due to the lack of the predetermination of relevant relational structure and to minimizing the probability of non-relational cues to correct objects' correspondences. This explanation seems to be in line with LISA incremental mapping algorithm (Hummel & Holyoak, 2003), which makes the mapping in the model very dependent on the importance assigned to propositions (Kubose et al., 2002).

The internal activation of a task's goal and proper application of this goal to the necessarily incremental reasoning steps seems to be critically in play during selection and encoding of relational information, thus also before structure mapping is initiated within WM. The partial support for this conjecture comes from Gordon & Moser's (2007) study of eye movements' paths in a picture scene mapping task, in which people first scanned each scene in a given pair for meaningful relations and engaged in structure mapping only thereafter. The strong effect of distraction obtained in this study, together with a lack of reliable interaction between distraction and saliency of relevant relations, suggest that the two manipulated control requirements imposed qualitatively separate constraints on WM during relational mapping. These constraints pertain to the ability to select information for the purpose of identifying relevant relations to reason with, and to the ability to deal with interference when processing these relations.

Further, the lack of reliable interaction between relational complexity and saliency of relevant relations gives a hint that the ability to select relations for analogy might be qualitatively distinct from the ability to integrate these relations within WM. Although both processes are about abstraction, which definitely requires WM resources, only the second seems critically dependent on the capacity of this system. Further research is needed to resolve this issue.

Finally, the reliable underadditive interaction between relational complexity and distraction was a surprise. This finding counters previous results of the opposite direction of this interaction in (Cho et al., 2007; Viskontas et al., 2004 and Richland et al., 2006). It is neither in line with LISA, in which WM capacity and efficiency of dealing with distraction both depend on the same inhibitory competition algorithm (Hummel & Holyoak, 2003), nor does it support the hypotheses that EC operates equally strong in different WM load conditions (e.g. Embretson, 1995). The possible explanation for this result could relate to the limitation of WM capacity (Cowan, 2005). Accordingly, since critical processing takes place only in the highly limited, most active part of WM, it could be speculated, that the strength of the detrimental effect of distraction on mapping is linked to the probability of distracters entering WM. Thus, the interference, which was caused by the "reversed" object-role bindings in the distraction-conditions of this experiment, should have been stronger, if the distracters were a part of the structure successfully accommodated into WM. This was surely more the case for easier (i.e. binary), than for more complex (quaternary) relations.

Summary and Future Directions

The current study sheds some new light on the nature of EC constraints in relational reasoning. The results demonstrate that next to dealing with distraction within WM, the goal-directed selection of information to enter structure mapping is an important, and to some extent, maybe a dissociable constraint. They also hint at a possibility that cross-mapping is only detrimental when affected structure is successfully accommodated within WM. Further research on the intricate contributions of EC to relational reasoning could combine measuring of individual differences in EC functions with experimental manipulation of their load in relational reasoning task. This could provide precise tests of plausibility of computational models of analogy-making.

Acknowledgments

This work was sponsored by the Polish Ministry of Science and Higher Education (grant 1422/B/H03/2009/36, years 2009-2010, awarded to Edward Nęcka and Anna Chuderska). The author wishes to thank Katarzyna Musiał for her assiduous help in data collection, Jarosław Kwiatkowski for implementing the test and Maciej Bernaś for reliable IT support in the lab.

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