Executive Control in Analogical Reasoning: Beyond Interference Resolution

Anna Chuderska (anna.chuderska@uj.edu.pl)
Adam Chuderski (achuders@apple.phils.uj.edu.pl)
Institute of Psychology, Jagiellonian University
al. Mickiewicza 3, 31-120 Krakow, Poland

Abstract

In recent studies, analogy-making has been shown to depend on the ability to resist interference. In our large-sample correlational study we found that efficiency of analogical reasoning is strongly related to measures of diverse executive control functions, far beyond interference resolution. These functions included interference resolution itself, but also: goal activation and application, inhibition of response tendency, and controlled visual search. The results implicate that executive control is an important factor for efficiency of analogical (and probably for most of types of relational) reasoning and that accounting for inter-individual differences in control and reasoning may be important for assessing the psychological plausibility of computational models of analogy-making.

Introduction

Analogy-making comprise high-level cognitive processes of structuring two phenomena (*analogs*, e.g. objects, events, ideas) by similar relations, even if they totally differ semantically or perceptually, and of inferring new goal-relevant information about one phenomenon (*target*) from elements of the second phenomenon (*source*) by means of finding out the systematic relational correspondences between them.

Ability to reason by analogy is essential in face of any novelty one needs to understand (e.g., in discovery) or to produce (e.g., in problem solving). Since seminal structure-mapping theory (Gentner, 1983) analogical reasoning processes have received much attention in cognitive science and contributed to more general theories of relational reasoning.

The major postulate of these theories is that processing relational representations is highly dependent on limited working memory (WM) capacity. Relational complexity theory quantifies this limit with the complexity of relations – the number of interacting variables that must be processed in parallel. The more variables have to be processed simultaneously, the higher task's difficulty is and the less people can solve it (Halford, Baker, McCredden, & Bain, 2005).

However, the more variables are active in WM, the bigger challenge arises to integrate them according to a goal, especially if they conflict across structural and semantic constraints (e.g. Markman & Gentner, 1993). So, it seems probable that even very capacious WM may be not enough to successfully analogize. For example, LISA – artificial neural network model (Hummel & Holyoak, 2003), which dynamically binds roles (i.e., arguments) and fillers (i.e., arguments' content) into relations by synchrony of firing their distributed representations, contains an intrinsic capacity limit (*phase set size*), since only a finite number of such role-filler bindings can oscillate asynchronously in one processing cycle. Thus, the model must control which units enter a current phase set and monitor its goal-progress. This is realized by lateral inhibition between competing units and by overall setup of relational representations, influencing the way activation spreads. If these discriminatory functions are weak, the model would be less efficient than its counterpart with the same phase-set size, but strong inhibition.

Thus, indispensible need to chose relational input and to manage distraction make some researchers (e.g., Viskontas, Morisson, Holyoak, Hummel, & Knowlton, 2004) believe that the fundamental source of constraints on human relational reasoning comes from the effectiveness of executive control over cognitive processing in WM during reasoning, instead of a sole structural limit in storage capacity. However, the role of executive functions in relational reasoning only begins to be explored in detail.

Moreover, despite the fact that efficiency of representing and manipulating relations is repeatedly differentiating participants (into those who are and who are not able to make the right analogy), there has been relatively little curiosity for exploiting this fact for identifying cognitive mechanisms underlying relational reasoning. Following others, we believe that, instead of averaging individual or group data, which leads to loosing important information, careful examination of inter-individual variability in reasoning by linking it to other tangible measures of lower-level cognitive abilities is a promising path for discerning cognitive mechanisms of reasoning (Lewandowsky & Heit, 2006).

Executive Control

Executive control (EC), also referred to as cognitive control, may 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. Executive processes are especially involved in novel situations, when arbitrary sequences of responses are to be emitted, when great amount of planning is required, when errors are likely and must be quickly corrected, and when dominant but not relevant response tendencies need to be overcome.

Recent theories assume that EC is an emergent process arising from dynamical interaction of many independent, elementary control mechanisms (e.g., Braver, Gray, & Burgess, 2007). A popular approach to EC is to identify executive functions. A taxonomy proposed by Miyake, Friedman, Emerson, Witzki, and Howerter (2000) includes three such functions: updating of WM, inhibition of dominant responses, and shifting. Updating consists in continuous "refreshment" of WM contents by inserting some stimuli to active memory while deleting others. Inhibition deals with volitional stopping of dominant but task-irrelevant thought or response tendency. Mental set shifting involves frequent alternating task-sets in WM. Other often postulated control functions, like random generation or planning were reduced to one of three former functions in confirmatory factor analyses. A function of dual-tasking, which requires coordination of two simultaneous mental or motor activities, could not be reduced to any function, and Collette and Van der Linden (2002) suggested that it is an independent ability. Some identified other executive functions: Duncan, Emslie, Williams, Johnson, & Freer (1996) observed that the ability to use indirect cues in order to activate and apply the proper goal was strongly decreased in unintelligent people and in frontal patients, even if they fully memorized and understood this goal.

However, the cited taxonomy to some extent reflects similarity and differences between executive tasks and lacks theoretical basis. Some authors posited that there are more fundamental control mechanisms that underlie performance in all previously postulated executive tasks. Kane and Engle (2004) identified two elementary control mechanism. One is active maintenance of a current goal or processing context that biases processing relevant to this goal or context. The other is monitoring and resolution of conflicts between cognitive processes or response tendencies. In a neurobiologically oriented proposal, Braver et al. (2007) named these two control faculties as proactive and reactive control. The work on cognitive architectures like EPIC (Meyer & Kieras, 1997) also suggests that the same set of control mechanisms may be involved in qualitatively different executive tasks. So, one important question is whether EC effectiveness as measured by the most popular executive tasks (WM updating, inhibition, interference resistance, task switching, dual-task coordination, and goal application tests) forms a set of diverse abilities or it results from the effectiveness of more basic mechanisms underlying EC.

Executive Functions in Analogical Reasoning

Another question deals with the involvement of EC in analogical reasoning. In their seminal study, Carpenter, Just, and Shell (1990) computationally modeled the cognitive processes needed in generic relational reasoning task - rule induction in fluid intelligence test's matrices (Raven's Progressive Matrices, RPM) - with two models that qualitatively differed in control ability instantiated in activating and managing subgoals during reasoning process and in coping with conflicts among multiple goals. Simpler version of the model, which used standard processes believed necessary for solving easy and medium RPM, was able to reach performance of an averagely intelligent human but failed to solve correctly 33% of problems given. The version extended by productions for goal management and for resolving conflicts among alternative goals solved all problems, thus simulating the results of highly intelligent humans. Extra WM capacity improved processing a bit, but it was not sufficient to fully substitute the effects of increased EC.

Executive productions in the above model were, however, slightly different from the current notion of EC. Recent studies provided more direct evidence that efficiency of relational reasoning is linked to EC. Gray, Chabris, and Braver (2003) observed that brain activity in neural structures responsible for interference resolution, invoked by high-interference condition of WM updating task, correlated with performance on RPM. Rich evidence for links between abstract reasoning tests and response inhibition and interference resolution was reviewed by Dempster and Corkill (1999). It was also shown that relational mapping is worse in a dual-task condition, especially if the concurrent task itself involved EC (Morrison, Holyoak & Truong, 2001).

Moreover, if superficially similar objects are placed in different relational roles in to-be-mapped structures, effective interference resolution seems necessary to overcome observed relational mapping impediment (e.g. Markman & Gentner, 1993). Cho, Holyoak, and Cannon (2007) manipulated the level of internal complexity and interference of an analogical mapping task, demonstrating that young participants' reaction times increased with relational complexity and interference. Similar decreases in performance when featural distraction occurred were observed in older adults (Viskontas et al., 2004). However, in both studies subjects compared analogy terms according to provided, not single-handedly identified, relevant variables, what could have potentially revealed other facets of EC. When Markman & Gentner (1993) encouraged subjects to compare more objects across analogs, it resulted in increased proportion of relational responses, aiding selection of what should enter structural alignment. Likewise, overriding initial mappings, if they turn incorrect (Keane, 1997), might call not only for inhibition, but also for goal-management mechanisms.

So far, correlational tests directly relating analogical reasoning to diverse executive functions were not, to our knowledge, administered. Most of previous experimental research on EC in analogy-making focused on interference resolution. Thus, the second question is whether significant correlations between analogizing and different aspects of EC beyond interference resolution can be observed and, if so, which executive measures will be linked to the efficiency of reasoning and how strong would this correlation be.

The aim of our study is to test a large sample of participants on an analogical reasoning task and on a few EC tasks, in order to look into common variance between EC measures and to test which EC scores (taken as indices of low-level processes) predict analogical reasoning score (understood as the index of a higher-level, compound process). This strategy may lead to identification of EC factors that most probably take part in analogical reasoning.

The Study

Two versions of paper-and-pencil Figural Analogy Test designed in our lab (Orzechowski & Chuderski, unpublished manuscript) were administered. They differ in relational complexity of items contained. We used four typical tasks tapping EC (Colette & Van der Linden, 2002): WM updating, response inhibition, shifting, and dual-tasking tests. We also used three tasks that also seem to impose significant but conceptually different requirements on EC: Duncan et al.'s (1996) monitoring task involving goal activation and application, resistance-to-interference task, and controlled search task. We used Raven's Progressive Matrices Advanced Version (60 min. time allowed) in order to check if our analogy test is a valid test of relational reasoning.

Method

Participants Participants in this study were 111 students (age = 18-46 years, M = 22.7, S.D. = 3.5, 63 females) recruited from colleges in Łódź, Poland. All participants reported no previous knowledge of the tasks used in the study. Each participant was paid 40 PLN (~10 EUR) for participation.

Figural Analogies Test The FAT (abbr.) test consists of two parts (versions), 24 items each, including figural analogies in a form ‘A is to B as C is to X’, where A, B, and C are types of figures, A is related to B according to one or two (in the low relational complexity version of the test) or three, four, or five (in the high complexity version) latent rules (e.g., symmetry, rotation, change in size, color, thickness, number of objects, etc.), and X is an empty space. The participant’s task was to chose one figure, out of four choice alternatives, that related to figure C, as B related to A. A sample test’s item is presented in Figure 1. Participants had 36 minutes to complete the former version of the test, and then they had 45 minutes to complete the latter. The total number of correct choices in each version of the test was used as ANALOGY-LOW and -HIGH scores, respectively.

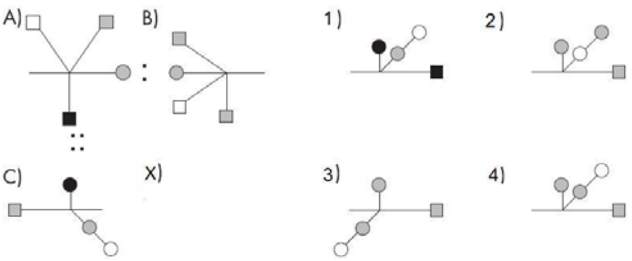

Figure 1: A sample item from Figural Analogy Test. The correct answer is the choice alternative no. 4.

WM Updating A modified n-back task was adapted for the study. In the task, a two-digit number (excluding palindromes, i.e. 11 & its multiplicities) was presented at random in the center of the computer screen, for 2 s apiece (+ 0.5 s for a mask). In each of six sessions, 16 out of 136 presented stimuli were repeated randomly on 1-, 2-, 3-, and 4-back positions (i.e., four repetitions for each *n* value in one session). The participants were instructed to update in memory only the most recent numbers and to press a response button only when recognizing a number repetition. A black square presented after a repeated stimulus informed participants that the stimulus was a target. A sound beep indicated false alarm errors. The participants took one practice session before taking the test. Total number of omission and false alarm errors was used as an UPDATING score.

Response Inhibition This task required inhibition of prepotent response and was analogous to stop-signal task (Logan & Cowan, 1984). Subjects were required to categorize digits into odd or even by pressing the proper of two but-tons. In a training phase they had to categorize 30 stimuli, presented randomly in the center of the computer screen. In an experimental phase, participants were asked to continue categorization for 186 stimuli (each presented for 3 s + 0.5 s for a mask) with the same category-button associations, except for 30 randomly chosen stimuli which appeared surrounded by a border. In that case subjects were required to emit opposite response. A total number of errors in the ‘border’ condition was taken as an INHIBITION score.

Task switching Alternating runs (Rogers & Monsell, 1995) task was used. Fixed length sequence of three letters (from set of eight possible letters) was presented randomly in the center of the computer screen. Depending on presented cue, one of two tasks should be performed. Task alternated predictably from sequence to sequence. In one task, subjects were to categorize stimuli into vowels or consonants, in the other they were to press one button if a letter contained angles (A, E, K, N) and another if it did not (C, O, S, U). There were 144 stimuli presented in total, 3 s were given for response in each trial. A difference (e.g., an error switch cost) in a number of errors for the first letter in a sequence (switch trial) and mean number of errors for the second and third letter (repeat trials), was taken as a SHIFTING score.

Dual task coordination In each trial of this task (Chuderski & Nęcka, in press) four random stimuli in the center of the computer screen were presented for 4 s, composed in 2×2 matrix with two digits on one random diagonal and two letters on the opposite one. Subjects were required to simultaneously compare the digits, checking if they both are odd (if they were, a left button should be pressed with the left hand), and the letters, checking if they both were identical (if so, a right button should be pressed with the right hand). There were four conditions: (1) ‘press nothing’ when one or two digits were even and the letters differed, (2) ‘press the left button’ – both digits were odd but the letters differed, (3) ‘press the right button’ – one or two digits were even but the letters were identical, and (4) ‘press both buttons’ – both digits were odd and the letters were identical. Stimuli were presented for 4 s plus 0.5 s for a mask. 80 trials of each condition were presented (320 in total) at random. A total number of errors was taken as a DUAL-TASKING score.

Goal monitoring We designed a version of Duncan et al.’s (1996) task for monitoring goal change. We continuously presented pairs of figures. The task consisted in categorization of a figure either on a left or on a right side into triangles or polygons. A symbol (a cue) presented between figures every several pairs determined which side is the relevant one. The cue informed by either directly showing the side (‘<’ or ‘>’ symbols) or by reminding the relevant side indirectly (‘=’ indicated ‘stay on the same side’, ‘+’ meant ‘change sides’). Subjects were expected to continuously monitor and apply the change of goal. A total number of errors in indirect condition was taken as a GOAL CHANGE score.

Interference Resolution We used two task’s versions. In flankers task, a triangle or a quadrangle was randomly presented in the center of the computer screen. Each stimulus was to be categorized with left (for quadrangles) or right (for triangles) mouse button press. Each stimulus was surrounded by six identical stimuli (so-called flankers), three on its left and three on its right side. 120 seven-stimuli patterns were presented during the task, random 60 of them were congruent (center stimulus was the same type of figure as flankers) while 60 patterns were incongruent (center stimulus differed from flankers). In another task, the stimuli were large letters (12 × 18 cm in size) falling under two categories (vowels: O, E, or U, or consonants: L, P, or H). Each stimulus was composed of the matrix of 9 × 9 smaller letters that could be congruent (i.e., from the same category as the large letter) or incongruent (from the opposite category). 80 stimuli were presented, random half in the congruent and remaining half in the incongruent conditions. The participants took one short practice session before each task. The documented effect in both tasks is that RTs in the incongruent condition are longer than in the congruent one. Thus, mean interference resistance cost in ms, measured with difference in latencies in incongruent and congruent conditions, was taken as an INTERFERENCE score.

Visual Search A matrix of 324 (18 × 18) geometric figures (each 1 × 1 cm in size) was presented for 3 min. Among exemplars of several figure categories, the matrix included 15 exemplars of a figure described as a target in the instruction presented before presenting the matrix. The participants' task was to position a cursor on each target stimulus and to click a mouse button as quickly as possible. One practice and three experimental sessions were administered. In each session a different target was used. Mean latency in seconds to click a target was used as a VISUAL SEARCH score. If a participant did not manage to find all the targets in a session, maximum value of 12 seconds (i.e., 3 minutes divided by 15 targets) was used as the score for that session.

Procedure The tests were administered in groups of 2 to 4 participants, on two consecutive days, in sessions lasting 5 hours each. Before each test participants were given written instructions. During computerized tasks administered on PC workstations each participant, with headphones on, was accompanied by one experimenter. The tasks were given in fixed order to minimize any impact on their intercorrelations. Two insight problem solving tests, described elsewhere (Paulewicz, Chuderski, & Nęcka, 2007), and five additional computerized tasks were also administered. One of the tasks was almost identical to the updating task and four remaining ones were unsuccessful, so we skip results from these tasks in the presentation of following analyses.

Results

Two missing UPDATING scores were substituted with means. Statistics for all scores are presented in Table 1. As INHIBITION, DUAL-TASKING, and GOAL CHANGE scores revealed Poisson distributions, in following analyses we use their logaritmized values closer to normal distribution. Reliability of both versions of analogy test was high (Cronbach αs = .76 and .78, respectively), and when α was calculated for the whole analogy test, it was equal as RPM reliability (.87 and .88, respectively). The easiest item of Analogy Test was solved correctly by 97.3% participants, while the most difficult item – by 18.9% of them (a chance level is 25%). All scores indicate large individual variability among participants, both in reasoning tests and in EC tasks.

Table 1: Descriptive statistics for all scores.

Score	Min	Max	M	SD	Skew
1.UPDATING	15	93	51.3	17.1	0.26
2.INHIBITION	0	19	4.1	3.7	1.54
3.SWITCHING	-2	16	2.8	3.4	1.23
4.DUAL-TASKING	0	97	17.0	14.1	2.36
5.GOAL CHANGE	0	46	6.5	9.2	1.95
6.INTERFERENCE	-73	346	33.9	70.9	2.50
7.VISUAL SEARCH	1.9	11.9	5.1	1.8	1.07
8.ANALOGY-LOW	7	24	18.5	3.8	-1.01
9.ANALOGY-HIGH	4	23	16.7	4.1	-0.69
10. ANALOGY	13	47	35.2	7.2	-0.81
11.RAVENS	10	36	25.0	6.1	-0.29

Correlations among scores are presented in Table 2 (scores from both versions of FAT were aggregated to one score). FAT score highly correlated with RPM score, so the former test is an apt measure of abstract relational reasoning. Analogy test significantly correlated with all postulated measures of executive functioning. The highest predictor of ANALOGY was Duncan's goal monitoring task score. Correlations between executive measures indicate significant source of common variance among five measures (1-5), while distractor interference and visual search were not much related to these tasks, probably due to their more perceptual nature. An interesting question arises whether statistical control over variance in one of the intercorrelated tasks will influence correlations pattern between remaining EC tasks' scores and ANALOGY score.

Table 2: Correlational matrix between all scores.

Score	1	2	3	4	5	6	7	8
1.UPDT.	1							
2.INHB.	**.41**	1						
3.SWCH.	**.30**	**.28**	1					
4.DUAL	**.31**	**.37**	**.27**	1				
5.GOAL	**.48**	**.28**	**.38**	**.40**	1			
6.INRF.	**.18**	.05	.04	**.17**	**.26**	1		
7.SRCH.	.10	.08	.06	.02	.09	.02	1	
8.ANLG.	**.42**	**.44**	**.33**	**.34**	**.56**	**.30**	**.25**	1
9.RAVN.	**.41**	**.36**	**.38**	**.29**	**.51**	**.30**	.06	**.76**

Note: Abbreviations match names from Table 1. For simplicity, we present absolute values of correlations between reasoning test scores and EC scores (all these rs were negative). Significant correlations at $p < .05$ level are printed in bold. Values of r higher than .24 are significant at $p < .01$ level.

After controlling for GOAL CHANGE variable (which yielded the strongest link to ANALOGY) the following results (Table 3) were observed. From six EC scores which intercorrelated previously, only some correlations with INHIBITION variable remained significant.

Table 3: Correlations after controlling for GOAL CHANGE

Score	1	2	3	4	6	7	8
1.UPDT.	1						
2.INHB.	**.32**	1					
3.SWCH.	.14	**.20**	1				
4.DUAL	.15	**.30**	.14	1			
6.INRF.	.08	.02	.07	.08	1		
7.SRCH.	.16	.11	.03	.01	.04	1	
8.ANLG.	**.21**	**.35**	.15	.15	**.19**	**.24**	1
9.RAVN.	**.22**	**.26**	**.23**	.12	**.21**	.01	**.67**

Note: The same convention as in Table 2 applies.

In next analysis (see Table 4), we statistically controlled for INHIBITION and GOAL CHANGE variables.

Table 4: Correlational matrix after controlling for GOAL CHANGE and INHIBITION variables.

Score	1	3	4	6	7	8
1.UPDT.	1					
3.SWCH.	.08	1				
4.DUAL	.06	.09	1			
6.INRF.	.10	.06	.09	1		
7.SRCH.	.14	.05	.02	.04	1	
8.ANLG.	.10	.09	.05	**.22**	**.30**	1
9.RAVN.	.14	**.19**	.04	**.22**	.04	**.64**

Note: The same convention as in Table 2 applies.

Now, neither updating, switching, and dual-tasking scores are significantly intercorrelated nor are they linked to analogical reasoning. Only two scores for perceptually oriented executive tasks, interference resistance and visual search, still significantly correlate with reasoning measure.

Correlational analyses suggest that in regression of analogical reasoning only part of EC scores may be significant predictors of ANALOGY score. Results confirmed this expectation. Only these scores entered a stepwise regression model: GOAL CHANGE ($\beta = -.34$, $p < .001$), INHIBITION ($\beta = -.30$, $p < .001$), VISUAL SEARCH ($\beta = -.26$, $p < .001$), and INTERFERENCE ($\beta = -.18$, $p < .02$). The significant predictors accounted for 46.8% of variance (corrected R^2). The model was significant, $F(5, 105) = 20.34$, $p < .001$.

Exploratory factor analysis revealed that all measures but VISUAL SEARCH (loading = .01) were moderately loaded by one higher-level factor (loadings ranged from .34 for INTERFERENCE to .76 for GOAL CHANGE), which can be interpreted as a general executive control ability. With the use of confirmatory factor analysis (CFA) we tested if the model including all executive measures explains data better than a more parsimonious model including only two measures: GOAL CHANGE and INHIBITION, which seem to capture two postulated basic control mechanisms (i.e., goal maintenance and response conflict resolution, respectively) to the greatest extent. The former CFA model, which included EC latent variable (loading all executive measures) and analogy latent variable (loading two analogy scores), had a very good fit ($\chi2 = 19.79$, df = 19, p = .407, $\chi2$/df = 1.04, AGFI = .926, RMSEA = .047). The latent variables were highly correlated (r = .82). However, more parsimonious model had almost perfect fit ($\chi2 = 0.29$, df = 1, p = .586, $\chi2$/df = 0.29, AGFI = .986, RMSEA = .010), with latent factors being indistinguishable (*r* = 1.0). Although the latter model, due to only two measures for each latent factor, most probably overestimated the correlation value between both abilities, it clearly supports two hypotheses stating that (1) executive control significantly underlies analogical reasoning and that (2) executive control may be aptly captured by measuring goal maintenance as well as response conflict resolution, which seem to be two crucial EC mechanisms.

Discussion

Presented results indicate that effectiveness of analogical reasoning is highly inter-individually varied and significantly linked to most of executive functions. However, contribution to variance in analogical reasoning by three of functions (WM updating, switching, and dual-tasking) was accounted for by two other, most highly correlated ones: goal monitoring and application and response inhibition. These results can be explained by virtue of Kane and Engle's (2004) and Braver et al.'s (2007) theories of dual mechanisms of EC, postulating goal maintenance and application as well as response conflict resolution as two main processes underlying other EC functions. Duncan's task may be a relatively pure measure of the former mechanism while the stop-signal task may be a good measure of the latter. Two executive functions that seem to control peripheral rather than central processes, namely resistance to interference and visual search, seem to be independent from postulated mechanisms of EC and they are moderately related to the effective processing of relations in the figural test. They may instantiate general low-level interference resolution and selection mechanisms which seem to be critical in relational reasoning, proven to be strongly constrained by semantics. Scores in elementary tasks imposing various control requirements but not imposing huge load on WM capacity predicted almost half of variance in analogical reasoning on figural material, proving that EC constraints pose the important cognitive limit on relational reasoning beyond WM storage limits.

Although our approach was correlational, and thus it does not allow for drawing causal conclusions, in our opinion it anyway constitutes a fruitful heuristic for further experimental and computational research on the nature of elementary mechanisms underlying the highly complex process of relational (including analogical) reasoning.

Our research confirms intuitions that resource-demanding relational integration (i.e., representing and manipulating relations in WM), should not be treated uniformly, as it can depend, next to WM capacity, on some conglomerate of basic EC functions of proactive (reasoning goal's monitoring & application) and reactive (inhibition of irrelevant relational bindings not complying with a goal) control, which may belong to functionally and computationally distinct sets of abilities. The same applies to the interference resolution, which might not only be about inhibition of distracting information in current WM content, but also pertain to selection of what enters WM. Before being assessed on relevancy to reasoning task, all representational elements (in memory or in stimuli) potentially compete for processing, especially if semantics can so easily blur structural patterns. Thus, a general notion of interference resolution may pertain to two specific mechanisms of choice: distractors' inhibition in WM and selection of relevant input for WM.

Summary and Future Directions

We attempted to connect the state of the art in research on EC with the efforts to identify cognitive mechanisms of relational reasoning. It seems that variability in analogical reasoning is almost in half underlain by a set of functionally distinct, but intercorrelated executive control functions, which are far more specific than it is usually recognized in analogical reasoning theory and research. Our initial, correlational study calls for more decisive experimental evidence on how EC contribute to analogical reasoning. This research should combine measuring of individual differences in EC functions with experimental manipulation of their load in relational reasoning task and it can bring precise tests of plausibility of computational models of analogy-making.

Acknowledgments

This work was sponsored by Polish Ministry of Science and Higher Education (grant N106 2155 33, y. 2007-2010, to E.Nęcka). Authors thank Radek Wójcik for conducting the experiment and Borysław Paulewicz for statistical advice.

References

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory variation: Dual mechanisms of cognitive control. In A. R. A. Conway. C. Jarrold, M. J. Kane, A. Miyake, & J. N. Towse, *Variation in working memory* (pp. 76-108). Oxford: Oxford University Press.

Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices test. *Psychological Review, 97*, 404-431.

Cho, S., Holyoak, K.J., & Cannon, T.D. (2007). Analogical reasoning in working memory: resources shared among relational integration, interference resolution, and maintenance. *Memory and Cognition, 35*, 1445-1455.

Chuderski, A., & Nęcka, E. (in press). Intelligence and cognitive control. In A. Gruszka, G. Matthews, & B. Szymura (Eds.), *Handbook on individual differences in cognition*. New York: Springer Verlag

Collette, F., & Van der Linden, M. (2002). Brain imaging of the central executive component of working memory. *Neuroscience & Biobehavioral Reviews, 26*, 105-125.

Dempster, F. N., & Corkill, A. J. (1999). Individual differences in susceptibility to interference and general cognitive ability. *Acta Psychologica, 101*, 395-416.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology, 30,* 257-303.

Engle, R. W., & Kane, M. J. (2004). Executive attention, working memory capacity, and a two-factor theory of cognitive control. In B. Ross (Ed.), *The psychology of learning and motivation, 44, (pp. 145-199).* New York, NJ: Elsevier.

Gentner, D. (1983). Structure-mapping: A theoretical framework for analogy. *Cognitive Science, 7*, 155-170.

Gray, J. R., Chabris, C. F., & Braver, T. S. (2003). Neural mechanisms of general fluid intelligence. *Nature Neuroscience, 6,* 316-322.

Halford, G. S., Baker, R., McCredden, J. E., & Bain, J. D. (2005). How many variables can humans process? *Psychological Science, 16*, 70-76.

Hummel, J. E., & Holyoak, K. J. (2003). A symbolic-connectionist theory of relational inference and generalization. *Psychological Review, 110*, 220-264.

Keane, M. T. (1997). What makes analogy difficult? The effects of order and causal structure on analogical mapping. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 946-967.

Logan, G. D. & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*, 295-327.

Lewandowsky, S., & Heit, E. (2006). Some targets for memory models. *Journal of Memory and Language, 55*, 441-446.

Markman, A., & Gentner, D. (1993). Structural alignment during similarity comparisons. Cognitive Psychology, 25, 431-467.

Meyer D., Kieras D. (1997) A computational theory of executive cognitive processes and multiple-task performance. Part 1: Basic mechanisms. *Psychological Review, 104,* 3-65.

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., & Howerter, A. (2000). The unity and diversity of executive functions and their contributions to complex „frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49-100.

Morrison, R. G, Holyoak, K. J., & Truong, B. (2001). Working memory modularity in analogical reasoning. In J. D. Moore, K. Stenning (Eds.), *Proceedings of the Twenty-Third Annual Conference of Cognitive Science Society* (pp. 663-668). Mahwah, NJ: Erlbaum.

Orzechowski, J., & Chuderski, A. (unpublished). *TAO Figural Analogy Test: Test & manual.* Krakow: Institute of Psychology, Jagiellonian University.

Paulewicz, B., Chuderski, A., & Nęcka, E. (2007). Insight problem solving, fluid intelligence, and executive control: A structural equation modeling approach. In S.Vosniadou, D. Kayser, & A. Protopapas (Eds.), *Proceedings of the 2nd European Cognitive Science Conference (pp. 586-591).* Hove: Laurence Erlbaum.

Rogers R. D., Monsell S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General, 124,* 207-231.

Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition and analogical reasoning in older adults. *Psychology and Aging*, *19*, 581-591.