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Working-memory modularity in analogical reasoning

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Abstract

We present several experiments using dual-task (DT) methodology to explore use of working memory (WM) during analogical reasoning. Participants solved verbal and figural analogy problems alone or while performing articulatory suppression (AS), spatial tapping (ST) or verbal random generation (VRG). As in other studies of relational reasoning we found that VRG disrupted both verbal and figural analogy performance. In addition, we found disruption of analogy performance by WM slave system distractors (i.e., AS and ST) consistent with the dominant modality of the analogy task. These findings are discussed with respect to Baddeley's model of WM and other studies of WM involvement in relational reasoning.

Introduction

Central to the ability to reason by analogy is the ability to form and manipulate mental representations of relations between objects and events. For instance, in a verbal analogy such as:

BLACK:WHITE::NOISY:QUIET

the reasoner needs to form mental representations of the relation between BLACK and WHITE (black is the opposite of white) and map it to the second pair in order to verify that the analogy is appropriate. Thus, BLACK:WHITE is mapped to NOISY:QUIET and the analogy is successfully solved. It has long been assumed that this type of process requires the use of WM (cf., Baddeley & Hitch, 1974); however, until recently relatively little attention has been given to how WM limits affect analogical reasoning (Halford et al., 1994; Hummel & Holyoak, 1992; Hummel & Holyoak, 1997; Keane, Ledgeway, & Duff, 1994). In the present paper we report experiments using dual-task (DT) methodology (employed extensively by Baddeley, 1986) to study the involvement of the various modules of WM in analogical reasoning.

Baddeley's (Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Logie, 1999) model of WM has dominated cognitive accounts of short-term memory for nearly three decades. The model consists of three components: the Phonological Loop (PL), the Visuo-Spatial Sketchpad (VSSP), and the Central Executive (CE). In Baddeley's model the PL and VSSP are modality-specific slave systems that are responsible for maintaining information over short periods of time. Baddeley (Baddeley & Hitch, 1974) originally conceived of the CE to account for functions of WM not performed by the PL and VSSP; however, Baddeley (1986) later embraced Norman and Shallice's (Norman & Shallice, 1986) Supervisory Attentional System as a possible model of the CE. Most recently, Baddeley (1996) has segmented the CE in an attempt to study its component processes. From this perspective the CE is responsible for (1) the capacity to coordinate performance on 2 separate tasks, (2) the capacity to switch retrieval strategies as reflected in random generation, (3) the capacity to attend selectively to 1 stimulus and inhibit the disrupting effect of others, and (4) the capacity to hold and manipulate information in long-term memory, as reflected in measures of WM span (Baddeley, 1996 p. 5). Baddeley suggests that the CE manages the work of WM while the slave systems actually maintain the information.

Also central to Baddeley's model is the concept of limited capacity. The slave systems and the CE share this limited capacity, such that increasing CE functioning would reduce the capacity of either the PL or VSSP to maintain information; however, there is evidence that each system may have its own limits as well (e.g., the PL capacity is limited by the amount of information that can be subvocally cycled in approximately two seconds).

Evidence for a multi-module WM system is copious, coming from both the cognitive and neuropsychology literatures. However, relatively little attention has been paid to the implications of WM for relational reasoning particularly analogical reasoning. Review of the functions of the CE as outlined above suggests that the CE should be critical for relational reasoning. Experimental evidence has confirmed this hypothesis for deductive reasoning, with random generation (e.g., Baddeley & Hitch, 1974; Gilhooly, Logie, Wetherick, & Wynn, 1993; Klauer, Stegmaier, & Meiser, 1997) and memory load (e.g., Baddeley & Hitch, 1974; Gilhooly et al., 1993; Toms, Morris, & Ward, 1993) both interfering with performance. Klauer et al. (1997) found that random generation interfered with spatial reasoning (transitive inference), and Waltz, Lau, Grewal, and Holyoak (2000) found that performing VRG or maintaining a concurrent memory load discouraged participants from using relational mappings in a task that can be solved via either featural or relational similarity (see Markman & Gentner, 1993, for a task description). What is not clear from these studies is what aspects of the DTs actually cause the interference in relational reasoning. At the very least, random generation involves task switching, memory insertion and storage, and relational binding of numbers with temporal location; whereas maintaining a concurrent memory load involves memory insertion and storage. Both tasks are very demanding on WM resources.

It is also not clear to what extent the WM slave systems are important for reasoning, particularly in situations where all the information is available visually to the reasoner. Gilhooly et al. (1993) and Toms et al. (1993) found no effect of PL- or VSSP-based DTs on propositional reasoning, while Klauer et al. (1997) found a small effect of articulatory suppression (AS; a PL secondary task) on reasoning latencies. It is important to note that in each of these propositional reasoning tasks all information necessary to complete the task was perceptually available in the task. For example, a propositional reasoning problem such as:

There is either a circle or a triangle.
Therefore, there is no triangle.

requires only the information presented to answer the problem. In contrast, a transitive inference problem such as:

The circle is to the right of the triangle.
The square is to the left of the triangle.
Therefore, the square is to the left of the circle.

requires the reasoner to generate a new proposition based on the information presented (i.e., left-of (square, circle)).

Similarly, Waltz et al. (2000) found that performing AS while performing the Markman and Gentner similarity task discouraged participants from using relational correspondences just as VRG did. A recent replication of this result in our lab showed that ST had an effect similar in magnitude to AS. Like the transitive inference task described previously, in order to make a relational choice propositions not immediately obvious from the stimuli must be generated. This characteristic is a hallmark of analogical reasoning. Thus, it is not clear at present to what extent the slave systems of WM are necessary for relational reasoning. It is likely that the modality and quantity of information that must be retrieved and relationally bound in order to perform a reasoning problem will determine which WM slave systems will be necessary.

Methods

To explore to what extent the various modules of WM are recruited in analogical reasoning, participants performed several relational reasoning tasks while performing one of several DTs. Participants in the AS condition were instructed to say the English non-word zorn once each second. Another group in the ST condition was instructed to tap four red dots in a clock-wise pattern one dot each second. Participants in the VRG condition were instructed to say a random digit from 0 to 9 once each second. A fourth group of participants served as controls, performing only the primary reasoning tasks. 96 undergraduate students from the University of California, Los Angeles participated in the study in exchange for course credit.

Verbal Analogy

In the verbal analogy (VA) task participants verified A:B::C:D analogies such as: BLACK:WHITE:: NOISY:QUIET (i.e., participants answered TRUE or FALSE). Analogy problems were based on those developed by Sternberg and Nigro (1980). A:B pairs were related by one of five common relations (antonyms, synonyms, category members, functions, or linear ordering). In TRUE problems, C:D pairs shared the same relation as the A:B pairs but were from a different domain than the A:B pair (e.g., color vs. sound). We created FALSE problems by substituting a D term that was related to C in a different way (e.g., linear-ordered (noisy, noisier) instead of opposite-of (noisy, quiet)).

Figural Analogy

In the figural analogy task (FA) participants verified A:B::C:D analogies based on Sternberg's (1977) People Piece Analogy (PPA) task. In PPA each item was a cartoon character that possessed one each of four binary traits (male/female, black/white, tall/short and fat/thin). TRUE analogies showed the same changes in traits between the A:B pair and the C:D pair as well as between the A:C pair and the B:D pair. Problems of varying degrees of relational complexity (RC, cf. (Halford, Wilson, & Phillips, 1998) were constructed based on the number of traits that were manipulated. RC=1 problems had only one trait manipulated across either the A:B or A:C pair. Thus, RC=1 problems were semi-degenerate, with only two repeated characters making up the entire analogy (see Figure 1a). RC=2 and RC=4 problems had either 1 or 2 traits manipulated across both the A:B and A:C pairs (for a total of either 2 or 4 total relations). Thus, RC=2 and RC=4 problems were non-degenerate, consisting of four unique characters in each problem (see Figure 1b). We created FALSE items by changing the Identity of one trait in the

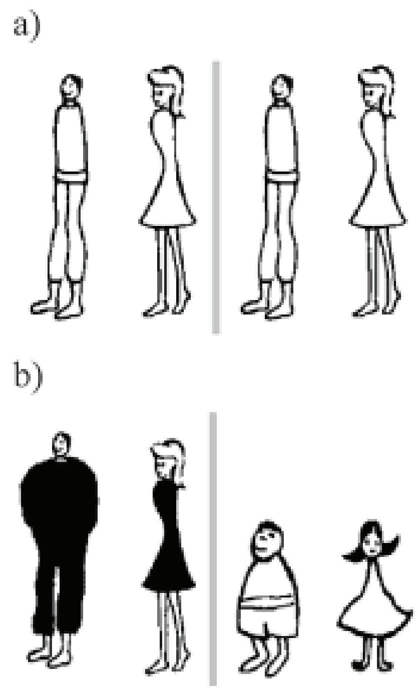

Figure 1: PPA figural analogy problems. a) semi-degenerate, RC=1, b) non-degenerate, RC=4.

fourth character so that it was not analogous.

Procedure

Reasoning problems were presented on a computer screen and participants indicated their response by pressing either a left or right foot pedal. Prior to beginning an experimental block, participants practiced their DT alone, the reasoning problems alone, and then practiced the two tasks together. Participants in the control group practiced the same total number of reasoning problems as participants in the DT groups. Reasoning problems were presented in three one-minute blocks. PPA problems were presented in blocks of increasing RC. The computer recorded analogy RT and accuracy as well as the frequency at which participants performed their DT.

Each block began with the participant pressing the right foot pedal. The participant was instructed to begin their DT. After 5s the first analogy problem appeared on the monitor. When the first problem appeared the experimenter began to hit a key each time the participant performed their DT. In this way the actual frequency and spacing of DT performance was recorded. After 60s a prerecorded voice told the participant to stop both tasks. The next block began after a 30s delay. After the final block the participant received instructions on the next task in the testing battery. The order of tasks was counterbalanced across participants.

Results

We predicted, as in past studies of both deductive (Gilhooly et al., 1993; Klauer et al., 1997) and analogical (Waltz et al., 2000) reasoning, that VRG would interfere with reasoning in both analogy tasks. We also predicted, as in a past study of transitive inference (Klauer et al., 1997) and analogy (Waltz et al., 2000), that DTs that interfered with WM slave systems corresponding to the modality of the task would interfere with performance. Thus, we expected that AS would interfere with VA performance and that ST and possibly AS (because of a verbal strategy frequently employed during PPA solving) would interfere with FA performance.

We analyzed both reasoning and DT performance from both the VA and FA tasks with between-subjects analysis of variance (ANOVA). In addition, we examined reasoning task performance by comparing control group performance to each of the DT groups using single DF planned comparisons.

Verbal Analogy

VA task performance is summarized in Figure 2. A between-subjects ANOVA revealed a reliable effect of DT type on accuracy (d-prime); F (3,92) = 4.5, MSE = .44, p = .005. Planned comparisons showed that AS and VRG had reliable effects on VA accuracy; t (46) = 3.7, p = .003 and t (46) = 2.8, p = .008, respectively. ST did not have a reliable effect on VA performance, t (46) = 1.1, ns. We conducted a similar analysis on RTs for the VA results. An ANOVA revealed a nearly reliable effect of DT type on VA RT; F (3,92) = 2.3, MSE = 979432, p = .085. Planned comparisons showed that VRG had a reliable effect on VA RT; t (46) = 2.3, p = .025. AS and ST did not have a reliable effect on VA RT; t (46) = .35, and t (46) = .96, respectively, both ns. DT data were analyzed using two metrics. First, a measure of DT frequency (mDT) was calculated for each subject (mean time between repetitions in ms). Second, a standardized measure of DT variance (vDT) was calculated for each subject (SD of time between repetitions divided by mDT). Participants performed AS (M =789 ms) and VS (M = 612 ms) faster than VRG (M = 1165 ms); t (69) = 4.4, p < .001. A second planned comparison showed that participants performing VRG were more variable in their performance than those performing AS or ST, even when the variance was corrected for the difference in mDT (vDT); t (69) = 3.2, p = .01. Thus, results for the VA task suggest that both the phonological loop (AS DT) and central executive (VRG DT) are important for performance of verbal analogies, with VRG producing a greater effect.

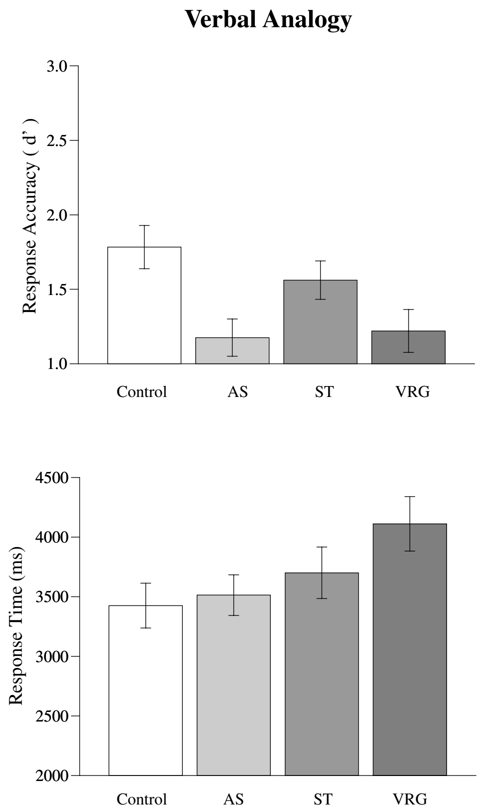

Figure 2: Accuracy and RT performance for verbal analogy under different dual-task conditions. Error bars reflect SEM.

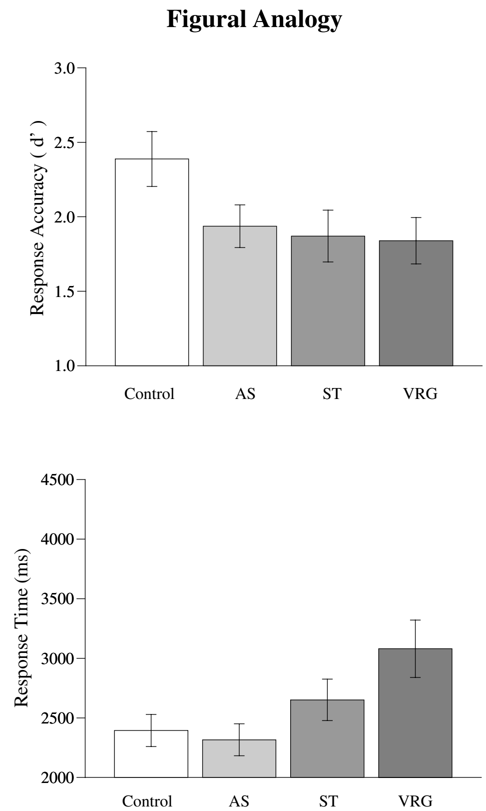

Figure 3: Accuracy and RT performance for People Pieces analogy under different dual-task conditions. Error bars reflect SEM.

Figural Analogy

FA task performance is summarized in Figure 3. A between-subjects ANOVA revealed a reliable effect of DT type on accuracy (d-prime); F (3,92) = 3.1, MSE = .65, p = .032. Planned comparisons showed that ST and VRG had reliable effects on FA accuracy; t (46) = 2.2, p = .036 and t (46) = 2.7, p = .01, respectively. AS had a marginal affect on FA accuracy; t (46) = 1.9, p = .059. We conducted a similar analysis on RTs for the FA results. An ANOVA revealed a reliable effect of DT type; F (3,92) = 3.8, MSE = 748368, p = .013. Planned comparisons showed that VRG had a reliable effect on RT for the FA task; t (46) = 2.5, p = .017. AS and ST did not have reliable effects; t (46) = 1.2 and t (46) = .41, respectively, both ns. Participants performed AS (M =1030 ms) and VS (M = 849 ms) faster than VRG (M = 1626 ms); t (69) = 2.6, p = .01. A second planned comparison showed that participants performing VRG were more variable in their performance than those performing AS or ST, even when the variance was corrected for the difference in mDT (vDT); t (69) = 2.5, p = .02. Thus, results for the FA task suggest that both the visuospatial sketchpad and central executive are important for performance of figural analogies, with the phonological loop perhaps playing a more minor role.

Discussion

In this study we have shown that WM slave systems can be recruited in the service of analogical reasoning and that the specific WM slave systems involved depend of the dominant modality of the task. This result agrees with a previous study of the affect of DTs on analogical reasoning (Waltz et al., 2000) and also of a similar study involving transitive inference (Klauer et al., 1997). All of these tasks have in common the need to generate propositional structures based on the information present in the problem.

In addition to the involvement of the WM slave systems we found robust effects of VRG on both verbal and figural analogies. This result is consistent with a growing body of findings for both deductive and inductive reasoning.

Multimodal vs. Unimodal Working Memory

Discussion of WM has traditionally been divided into two camps camps that are frequently divided by the Atlantic Ocean. The multi-modal camp (centered to the east of the Atlantic) has typically relied on DT methodologies, and results from neuropsychology and more recently neuroimaging. The uni-modal camp (centered to the west of the Atlantic) favors WM-span measures used as probes to investigate individual differences in language and reasoning. The current results, while not inconsistent with the capacity limits that are central to the uni-modal models, require a multi-modal model for a complete interpretation.

On first consideration, DTs such as AS or ST could simply require less WM resources than tasks such as VRG. Inductive reasoning tasks that require retrieval of semantic information and/or generation of additional propositions in WM may simply be more load intensive than propositional reasoning tasks in which all of the information necessary to solve the problem is perceptually available. Thus, AS and ST interfere with inductive reasoning and not propositional reasoning (at least the simple propositional reasoning problems typically used in DT studies). This account predicts that slave system tasks should interfere with reasoning less than VRG and also predicts no dissociation of PL or VSSP DTs if AS and ST interference is simply load dependent then the modality of the resource drain should not matter. The results of Waltz et al. (2000) argue against the weak form of this interpretation, in that AS and VRG produced equal interference in the analogy task. However, it is possible that the analogy measure used in their task (which shows a robust individual difference most likely not related to WM capacity) may not have been sensitive enough to pick up the differences in resource demand caused by AS and VRG. Also, performance on the secondary tasks was not assessed in that prior study.

The results reported here--showing a dissociation in slave system DT interference across analogy tasks of different modality--rule out this interpretation and argue for a multi-modal WM system that requires separate phonological and visuospatial systems. Specifically, the finding of strong interference by AS in the VA task with no corresponding ST interference argues that the PL is necessary for verbal analogy, while the VSSP is not. In contrast, the stronger interference of ST in the predominantly visual FA task compared to PL shows the opposite pattern of interference.

It is not clear from these results, however, what role the slave systems play in analogy. One possibility is that they are used to maintain relational information while it is organized into the propositional structures necessary for further relational processing. In this view, AS and ST DTs interfere with activation of the semantic or visual information necessary to solve the analogy task. This interpretation is consistent with Baddeley's view of the slave systems if one considers the role of the PL and VSSP to be maintenance of representations via continual firing of their mental representations in long-term memory (LTM), a conception proposed by Fuster (1997).

The Role of the Central Executive in Reasoning

One criticism of the multi-modal WM model has been the amorphous nature of the CE. However, a general consensus among researchers is beginning to emerge: the CE is viewed as important for task switching, inhibition of internal representations or prepotent responses, and the activation of information in LTM during an activity that requires the active manipulation of material. All of these functions appear to be critical for higher-level cognition--particularly relational reasoning. What this consensus fails to provide is a detailed account of how the CE actually performs relational reasoning.

Hummel and Holyoak (1997) proposed a model of how the CE may perform relational reasoning. This model, LISA (Learning and Inference with Schemas and Analogies), is an artificial neural-network model of relational reasoning. LISA uses synchrony of firing to bind distributed representations of relational roles (e.g., the roles of *opposite-of* (X, Y)) to distributed representations of their fillers (e.g., *black* and *white*). The process of "thinking about" a proposition, such as *opposite-of* (black, white), entails keeping separate role-filler bindings (e.g., those for black and those for white) firing *out* of synchrony with one another. According to LISA, WM is therefore necessarily capacity-limited: It is only possible to keep a finite number of role-filler bindings simultaneously active and out of synchrony with one another. The synchronized (and de-synchronized) patterns of activation representing propositions in LISA serve as the basis for memory retrieval, analogical mapping, analogical inference and schema induction. That is, all the operations of WM depend critically on the role-filler bindings in WM. As such, an important component of the "job" of the CE is to control which patterns enjoy the "privilege" of remaining active and mutually desynchronized. This process requires no homunculus to operate; rather, it is governed simply by the way that relational information is structured in LTM and the extent to which different mental representations are relationally similar.

According to LISA, a second function of the CE is to keep track of the correspondences between elements of the source and elements of the target (see Hummel & Holyoak, 1997). Algorithmically, LISA accomplishes this function by monitoring which units in the source fire in synchrony with which in the target. Hummel and Holyoak assume that this "keeping track" is performed by neurons in prefrontal cortex with rapidly-modifiable synapses (e.g.,Asaad, Rainer, & Miller, 1998; Fuster, 1997), and thus needs no greater executive control.

If these are the roles of the CE in relational reasoning, then why does VRG so potently interfere with reasoning? We argue that VRG requires exactly the same operations as relational reasoning. To produce a random stream of numbers it is important not only to know what numbers one has recently said (e.g., 3,8,2), but also the order in which one said them (e.g., 3,8,2,8,2,3 seems more "random" than 3,8,2,3,8,2; Baddeley, 1966, noted that as VRG performance breaks down di- and tri-grams start to emerge in the number stream). That is, it is necessary to bind the numbers to their serial position. According to LISA, VRG consumes exactly the kind of binding resources as the binding and mapping of relational information in WM. As a result, VRG disrupts analogical reasoning and other forms of relational reasoning.

Acknowledgments

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