

Time Course of Inhibitory Control During Analogical Reasoning: An Event-Related Potential Approach

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Abstract

Inhibitory control is an important aspect of analogical reasoning critically dependent on prefrontal cortex. We used a novel visual analogy paradigm with scalp electroencephalography (EEG) to explore several ways the brain uses inhibitory control to perform analogy. Previous studies have suggested that inhibitory control helps to manage working memory, so we used a separate task to measure individual differences in working-memory span to help us interpret differences in inhibitory control during reasoning. We found evidence that low working-memory span individuals likely lacked the necessary inhibitory control to keep unattended relations from entering visuospatial working memory early in processing. We also found that a late frontal event-related potential sensitive to relational distraction was differentially modulated in high and low working memory span individuals. These findings provide additional evidence for the importance of inhibitory control during analogical processing.

Keywords: analogy, working memory, inhibitory control, EEG, ERP

Introduction

Studies involving children (Richland, Chan, Morrison, & Au, 2010; Richland, Morrison, & Holyoak, 2006; Thibaut, French, & Vezneva, 2010a, 2010b), younger adults (Cho, Holyoak, & Cannon, 2007; Cho et al., 2010), older adults (Viskontas et al., 2004), and patients with damage to prefrontal cortex (Krawczyk et al., 2008; Morrison et al., 2004) have all provided evidence that inhibitory control in working memory (WM) is an important aspect of both visual and verbal analogical reasoning. Neuroimaging

studies of analogical reasoning have implicated areas in prefrontal cortex (PFC) as critical for semantic retrieval during analogy (Bunge, Wendelken, Badre, & Wagner, 2005), avoiding distraction from non-goal related relational information (Cho et al., 2010), and performing analogical mapping and similar types of relational integration (Bunge, Helskog, & Wendelken, 2009; Cho et al., 2010; Green et al., 2010; Morrison, Nikitin, Bharani, & Doumas 2012). Computational accounts of these data (Doumas, Morrison, & Richland, under review; Knowlton, Morrison, Hummel, & Holyoak, 2012; Morrison et al., 2004; Morrison, Doumas, & Richland, 2011; Viskontas et al., 2004) suggest that inhibitory control is central to the processes of semantic retrieval and analogical mapping; however, there is little direct experimental evidence for mechanisms by which inhibitory control is recruited during analogical reasoning.

WM has been thought to play a critical role during analogical reasoning (Halford, 1992; Morrison, 2005). Domain-specific as well as central-executive WM dual tasks interfere with analogical processing (Morrison, Truong, & Holyoak, 2001; Waltz, Lau, Grewal, & Holyoak, 2000). Likewise, individual differences in working-memory span (see Conway et al., 2005) are frequently related to matrix reasoning performance (e.g., Kane & Engle, 2002). In an effort to understand how inhibitory control may be involved in WM processing, Vogel, McCollough, and Machizawa (2005) asked participants with high and low WM span to perform a simple delayed match-to-sample WM task while their brain activity was observed using scalp encephalography (EEG). Vogel et al. identified a Continuous Negative Variation (CNV) event-related

potential (ERP) during the delay period in the task that correlated with the number of items the participants were required to hold in WM. Interestingly, when participants were asked to remember two items and ignore two others, the ERPs of high-WM span participants resembled those for two item trials, while those of low-WM span participants resembled those for four items. Thus, high-WM span individuals appear to be better at managing their WM using inhibitory control to suppress goal-irrelevant information. Shimamura (2000) has argued that his type of dynamic filtering appears to be a fundamental function of PFC.

Based on Learning and Inference with Schema and Analogy (LISA; Hummel & Holyoak, 1997, 2003), a neurally-plausible model of analogical reasoning, we have previously argued that inhibitory control is necessary throughout analogical processing (Morrison et al., 2004; Morrison, Doumas, & Richland, 2011; Viskontas et al., 2004). Specifically, inhibition plays a central role in (a) LISA's manipulation of relations in WM, (b) its ability to select items for placement into WM, (c) its ability to discover analogical mappings. Thus, we anticipate that inhibitory control will be evident in analogical reasoning, and may be modulated by the WM span of participants.

In an effort to explore two possible roles for inhibitory control during analogical processing, we developed an experimental paradigm for use with EEG (see Figure 1). On each trial, participants were cued to solve a visual analogy based on one of three abstract relations present in the stimuli. Critically, on some valid trials one of the unattended relations was not congruent. Participants need to ignore this relation to arrive at the correct solution. Thus, the task is similar to the version of the People Pieces analogy task we had developed for behavioral (Cho, Holyoak, & Cannon, 2007; Viskontas et al., 2004) and neuroimaging studies (Cho et al., 2010) except that participants were considering asymmetric relations as opposed to same-different relations. The task was also similar to Vogel et al. (2005), in that participants had a goal-relevant WM load (i.e., the to-be-attended-to relation) in the presence of potentially distracting information.

We had two central hypotheses. First, people lower in WM-span would be less efficient than higher WM-span individuals in keeping goal-irrelevant information out of visuospatial WM. Thus, we expected to see a more negative CNV (Vogel et al., 2005) in occipitoparietal regions in low WM-span individuals, indicating that they were storing more information in their WM than higher WM-span individuals who were efficiently filtering the goal-irrelevant information.

Second, we predicted that relationally distracting trials require the engagement of inhibitory control and thus should engage areas in inferior frontal cortex (e.g., Cho et al., 2010) to protect the analogical mapping process from goal-irrelevant information.

Method

Participants verified visual analogies constructed from shapes that possessed three varying properties (luminance, orientation, and number; see Figure 1). On each trial, participants were cued to attend to *only one* of the relations formed by the three properties. Participants decided whether the relation in the top pair was the same or different than the relation in the bottom pair. There were three conditions in this experiment: *Valid-No Distraction*, *Valid-Distraction*, and *Invalid*. In the *Valid-No Distraction* condition, all three relations were congruent between the top and bottom pair, with the correct answer being “yes” to indicate that the problem as cued was a valid analogy. In the *Valid-Distraction* condition, the cued property had congruent relations as in the previous condition; however, one of the two unattended relations was incongruent, thus creating a response conflict between the attended and unattended relation. *Invalid* trials were just like *Valid-Distraction* stimuli, except that participants were asked to attend to the relation that did not map.

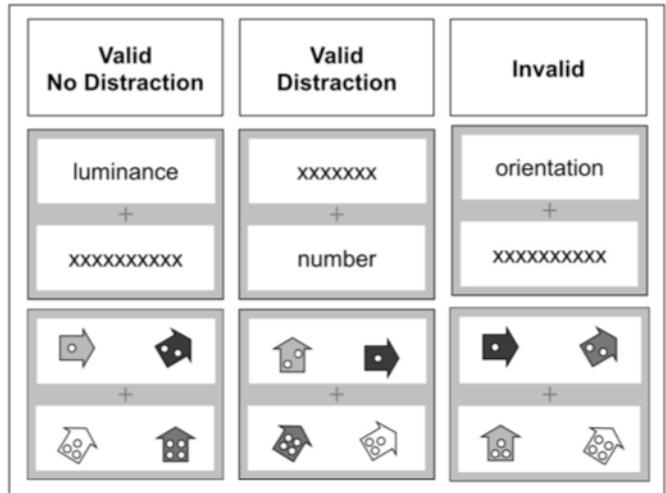


Figure 1: Participants saw analogy problems in one of three conditions. In “Valid–No Distraction” problems, participants mapped based on a single relation (e.g., luminance—the shapes get darker from left to right), while the other relations (e.g., orientation and number) could also be successfully mapped between pairs. In “Valid–Distraction” problems, participants once again were only required to map based on one relation (e.g., number—the number of dots in the shape decreased from left to right); however, one of the other relations present did not successfully map between pairs (e.g., luminosity in the source decreased from left to right, while it increased from left to right in the target). “Invalid” trials were like “Valid–Distraction” trials; however, participants were to map based on the invalid relation (e.g., orientation—the arrowhead of the shape rotated counterclockwise in the source, but clockwise in the target).

Participants

Twenty-nine undergraduate students from Loyola University Chicago participated in the experiment. Of the 29 participants three were omitted from the analysis because of poor EEG recording quality. The remaining 26 participants were divided based on median WM-span into two equally sized groups. The low-WM span group ($M = 33$, $SEM = 2$) had a WM span smaller than the high WM-span group ($M = 61$, $SEM = 2$; $t(24) = 7.5$, $p < .001$).

Participants gave informed consent to take part in the study. The Loyola University Chicago Institutional Review Board approved all recruitment methods and procedures.

Materials

Each analogy problem consisted of two pairs of geometric shapes (see Figure 1). Each shape had one of four levels of three parametrically manipulated properties: luminance, orientation, and number. Shapes were combined into pairs to create order relations with respect to the three properties. For instance, pairs of shapes could be increasingly bright or dark (luminance); rotate clockwise or counter clockwise (orientation); and increase or decrease in *number*. In any given problem a relation in the source (i.e., top pair) could either match or mismatch the corresponding relation in the target (i.e., bottom pair). A set of 144 unique stimuli was generated, 72 of which contained pairs of shapes with all congruent relations (used for Valid-No Distraction trials). The remaining 72 stimuli were divided into thirds, with each third having one mismatching relation in one of the three properties. For the problems containing a mismatching relation, if the participant was cued to attend to the mismatching relation the trial was Invalid, but if the participant was cued to attend to one of the matching relations the trial type was Valid-Distraction.

EEG Recording

Scalp electroencephalography signal (EEG) was recorded from each participant using a 38-channel Biosemi Active2 EEG system. 32 electrodes were located at standard 10/20 locations in a nylon-elastic cap. Two electrodes were placed on the left and right mastoid bones for subsequent digital referencing. To expand the coverage of EEG monitoring, we placed four electrodes on the face on the inferior and lateral aspects of the eye orbit. These electrodes were used to expand PFC electrode coverage and for ocular artifact correction and rejection. Unfiltered EEG was re-referenced to an average of the two mastoid electrodes and a 0.01 Hz high-pass filter was applied after recording. A band-stop filter from 59 to 61 Hz was also applied to the raw EEG to remove any AC electrical contamination. EEG signal was corrected for ocular artifacts using a spatial PCA filter corrected for the average noise level in the signal according a method available in EMSE (Source Signal Imaging, San Diego CA). Signal was further cleaned via a $\pm 100\mu\text{V}$

rejection criterion. Included participants have fewer than 15% of trials rejected due to EEG artifacts.

Procedure

After a participant was fitted with the EEG cap and electrodes, he or she sat in a soundproof chamber equipped with a 21-inch CRT monitor and an electronic response box controlled by a program written in e-Prime 2.0. The participant was positioned so that their head was 100cm from the monitor. The stimulus was adjusted to 4 degrees of visual angle. The participant then received task instructions followed by 24 practice trials with feedback. After completing these trials, the participant was asked if they had any questions, and then was reminded to respond as quickly and as accurately as possible and to blink only after a response was made.

Each trial began with a randomly jittered fixation screen that lasted 500 to 1000 ms. Then, the name of one of the three properties appeared near the fixation point (see Figure 1), also for 500 to 1000 ms, before it disappeared (for 500 to 1000 ms) and was replaced by the stimulus shapes, which remained visible until a button press was made. There were no systematic difference in any of these jittered times between conditions. The entire experiment consisted of 216 trials, and accuracy and response times (RT) were measured. Participants completed four blocks of 54 trials, with conditions and stimuli randomized within and across blocks. One-minute breaks were given between blocks, during which cumulative mean accuracy and RT were reported to the participant.

WM Span

After completing the visual analogy task, participants completed a 15-20 min operation span WM task (Conway et al., 2005). On each trial, participants were asked to verify a simple mental arithmetic problem and then were to remember a letter. Trials were from 2 to 7 problems/letters long. At the conclusion of a trial, participants were presented with an array of letters and were to click the letters in the sequence they were presented. WM span was defined as the total number of letters correctly remembered in the presented order. All participants performed the math problems at 85% correct or better.

Results

Behavioral Results

Because yes-valid/no-invalid responses were used, we report accuracy using d -prime¹. Participants were less accurate in the Valid-Distraction ($M=3.0$, $SEM= .13$) than the Valid-No Distraction ($M=3.2$, $SEM= .16$) condition $F(1,24) = 17$, $p < .001$, $\eta_p^2=.4$); however, there was no

¹ Hit rates of 1 were replaced with .99 and hit rates of 0 were replaced with .01 for purposes of calculating d -prime.

difference in RT between Valid-Distraction ($M=2.2$ s; $SEM=.08$) and Valid-No Distraction ($M=2.2$ s; $SEM=.09$; $F(1,24) = .001$, ns , $\eta_p^2 < .001$). Additionally, there was no interaction with WM-span group for either accuracy ($F(1,24) = .46$, $p = .5$, $\eta_p^2 = .02$) or RT ($F(1,24) = 1.3$, $p = .3$, $\eta_p^2 = .05$). Thus, we saw an effect of relational distraction even in these relational simple problems; however, this effect appeared not to be moderated by WM span.

EEG Results

Individual Differences in WM Our first predication was that WM-span would be reflected in the CNV (Vogel et al., 2005) in occipitoparietal regions. We believed this would result from low WM-span individuals' inferior ability to ignore goal-irrelevant information during analogical processing, similar to the effect observed by Vogel et al. (2005) during a delay period in a delay match-to-sample task. Consistent with this prediction we found that participants in the low WM-span group showed a more negative CNV (see Figure 2) from just after the occipital N1 wave (180ms) all the way through the end of task processing (1700ms; $F(1,24) = 7.1$, $p = .01$, $\eta_p^2 = .2$). This effect was not modulated by relational distraction ($F(1,24) = .2$, $p = .7$, $\eta_p^2 = .008$).

Effect of Relational Distraction Our second prediction involved the role of PFC in managing distraction during analogical mapping. Using a similar analogy task with fMRI, Cho and colleagues (2010) had previously shown areas in middle and inferior frontal gyri were sensitive to relational distraction. We further hypothesized that this effect would be late in processing, coincident with analogical mapping (Morrison et al., 2012). We did not find a main effect of relational distraction (see Figure 3; $F(1,24) = .6$, $p = .4$, $\eta_p^2 = .024$); however, we did find an area in right

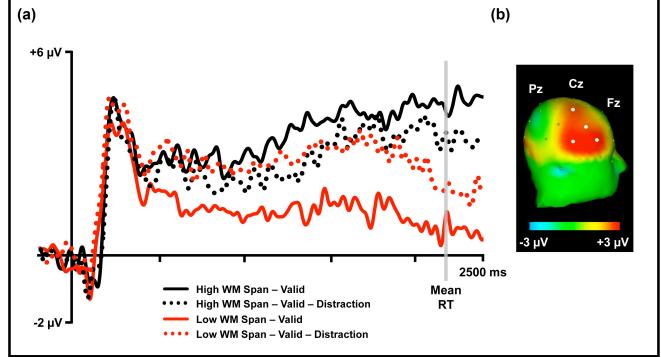


Figure 3: Modulation of the neural correlates of relational distraction by WM-span. (a) The Valid-No-Distraction ERP for low WM-span participants was significantly less positive than either the Valid-Distraction ERP for the same group, or either condition ERP for the high WM-span group in right frontal electrodes (indicated by white dots in Figure 3b). (b) Map showing double subtraction topography from 1000 to 1700ms post-stimulus.

PFC consistent with Cho et al. (2010) which showed an interaction between WM-span and relational distraction ($F(1,24) = 7.1$, $p = .01$, $\eta_p^2 = .2$). While the high WM-span group did not show a difference between the Valid-Distraction and Valid-No Distraction conditions ($F(1,12) = 5.1$, $p = .3$, $\eta_p^2 = .07$), the low WM-span group did ($F(1,24) = 1.0$, $p = .01$, $\eta_p^2 = .2$). Specifically, both conditions for the high WM-span group showed similar levels to the Valid Distraction condition for the low WM-span group, while the Valid-No Distraction condition for the low WM-span group was reliably less positive.

Discussion

In many real-world problem-solving situations, one may have to choose between multiple common relations for use as the source for an analogy. For instance, a molecular biologist may want to favor repeat sequences instead of common codons as the basis for an analogy between two genes. Attending to codons when one is looking for repeat sequences may be misleading, thus good attention to just the chosen relation (e.g., a repeat sequence) and inhibition of the irrelevant information (e.g., a specific codon) for the situation is most efficient. However, faced with a new situation, codons may now be the better relation to use, so the system must be flexible to solve the problem at hand. In the paradigm used in this study, reasoners were sometimes asked to favor the relation based on one stimulus characteristic over another as the basis for their analogy. However, their focus needed to be flexible because what was critical on one trial may be misleading on the next. Using this paradigm we demonstrated two ways in which inhibitory control can influence analogical processing.

First, as in Vogel and colleague's (2005) demonstration using EEG with a delayed match to sample task, we found

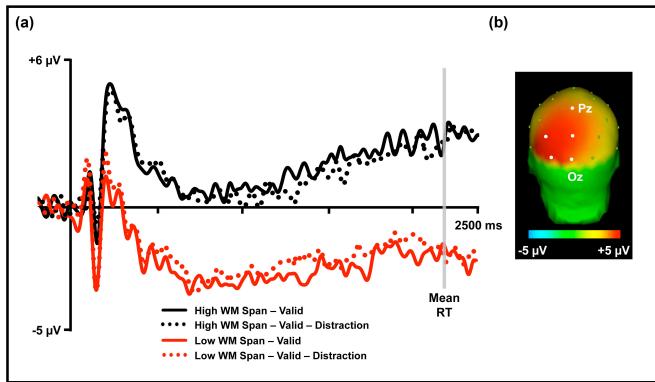


Figure 2: Modulation of the neural correlates of visuospatial working memory during analogical reasoning by WM-span. (a) A CNV ERP was more negative for the low than the high WM-span group in occipitoparietal electrodes (indicated by white dots in Figure 2b). (b) Map showing high minus low WM-span subtraction topography from 180 to 1700ms post-stimulus.

EEG evidence that low WM-span individuals allowed more information to enter visuospatial WM than high WM-span individuals. It is likely that this difference resulted from low-WM span individuals considering goal-irrelevant relations regardless of condition. This occurred early in the reasoning time course, beginning just after the first signals of spatial attention (i.e., the occipital N1), and continued throughout the trial time course. While, this did not result in a difference in behavioral performance on the task, one can imagine that in a more difficult task (e.g., at higher levels of relational complexity), this inefficient gating of WM may have behavioral consequences.

Secondly, we found sensitivity to relational distraction as measured by a subtraction between Valid-No Distraction and Valid-Distraction trials in a right frontal ERP was modulated also by WM-span. It appears that high WM-span individuals frequently engage this area of the brain during later stages of analogical mapping, while low WM-span individuals engage it more in the face of distraction. We believe this aspect of inhibitory control is likely distinct from the previous result. If high WM-span individuals are better at using early inhibitory control to gate WM from non-goal related information one might hypothesize that they would require the later PFC mechanisms less; however, it appears that high WM-span individuals use it consistently, and on average more than low WM-span individuals. In contrast, low WM-span individuals, could certainly make use of the PFC mechanism for Valid-No Distraction trials to focus on just the relevant relations; however, they don't, using it only when actual conflict is detected. Thus, the use of PFC seems to be more reactive in the case of low WM-span individuals, while it is more proactive with high WM-span individuals. Thus, this appears to be a second neural mechanism that favors high WM-span individuals.

This result is also consistent with the results from a previous fMRI study using a very similar task that identified areas in bilateral inferior frontal gyrus (IFG) as being more active during analogy in the presence of relational distraction (Cho et al., 2010). The EEG topography shown in Figure 3 is consistent with the activation reported by Cho and colleagues and also many other studies investigating the role of inhibitory control in WM (e.g., Goel et al., 2000; Goel & Dolan, 2003; Prado & Noveck, 2007; De Neys et al., 2008). Also, as in Cho and colleague's study the topography resulting from the distraction contrast appears to be at least partially distinct from the frontopolar area previously identified as being associated with analogical mapping via both EEG (Morrison et al., 2012) and fMRI (Green et al., 2010) methods. Future investigations will need to focus on how frontopolar PFC and IFG may interact in the service of analogical reasoning.

Several previous behavioral studies have shown evidence of the importance of inhibitory control during analogical reasoning in the face of distraction (e.g., Cho et al., 2007; Krawczyk et al., 2008; Morrison et al., 2004; Viskontas et al. 2004); however, these studies typically only found

reliable effects when distraction was present in more relationally complex problems.² In the present study we show the engagement of inhibitory control for even simple one-relation analogy problems. However, this effect was apparent only in the ERP results, and accuracy, not RT.

So what exactly does inhibitory control do during analogical reasoning? Given our results it is quite likely that the answer is not a unitary one. Likewise, in the LISA model of analogical reasoning (Hummel & Holyoak, 1997, 2003; Knowlton et al., 2012), the function of inhibitory control may be multifaceted, and may differ across the time course of processing analogies. Future neuroimaging studies will be driven by precise computational accounts of the neural mechanisms underlying analogical processing (e.g., Knowlton et al., 2012; Morrison et al., 2012) and will likely require EEG time-frequency analysis techniques to appreciate the temporal dynamics of the neural circuits responsible for analogical reasoning.

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² One notable exception is distraction effects during analogical reasoning in young children (Richland et al., 2006, 2010).

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