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

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Abstract

Developmental, neuropsychological, and neuroimaging studies have all suggested that inhibitory control in working memory (WM) is an important aspect of both visual and verbal analogical reasoning critically dependent on prefrontal cortex. However, very little is known about how inhibitory control contributes to analogy. In an effort to explore the time course of inhibitory control in analogy we developed an experimental paradigm for use with scalp electroencephalography (EEG). 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 other relations was not congruent. Based on previous EEG results showing that individual differences in working memory span correlate with differences in inhibitory control, we subdivided our participant group based on working memory span. Our results indicate that increasing distracting relational information modulated the N2 event-related potential, previously associated with inhibitory control. Further, EEG results also suggested that (as in a previous study using a simple delay match to sample paradigm) individuals with high working-memory span showed a modulation of inhibitory control during analogical mapping, whereas those with low working-memory span did not. These findings suggest that inhibitory control is integral to analogical processing, and that computational accounts need to explain the mechanisms by which inhibitory control is engaged during analogy.

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

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, 2012). Computational accounts of these data (Doumas, Morrison, & Richland, under review; Knowlton, Morrison, Hummel, & Holyoak, under review; 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) frequently predict matrix reasoning performance (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 monitored using scalp encephalography (EEG). Vogel et al. identified an 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, those of low-WM span participants resembled those for four items. Thus, it appears that inhibitory control is a fundamental mechanism of working memory functioning, and that this capacity is critically dependent on PFC (Shimamura, 2000).

Based on Learning and Inference with Schema and Analogy (LISA; Hummel & Holyoak, 1997, 2003), a neutrally-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 measure the time course of inhibitory control, 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 other relations was not congruent. Thus, participants need to ignore these relations 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; Morrison et al., 2001; Viskontas et al., 2004) and neuroimaging studies (Cho et al., 2010) except that participants were considering abstract asymmetric relations as opposed to same-different relations. The task was also similar to Vogel et al. (2005), in that one condition required ignoring information that was important on other trials, but was not goal-relevant on a particular trial. Like Vogel et al. we also tested participants with both high and low WM span.

We hypothesized that (after early visual processing) neural evidence of inhibitory control would be present throughout problem solving. Specifically, we expected to observe a greater N2 ERP on distraction trials relative to those with all congruent relations. The N2, a negative wave peaking shortly after early sensory processing, typically with frontal topography, has been considered to be an index of early engagement of inhibitory control (Folstein & Van Petten, 2008). We also anticipated that evidence of inhibitory control would continue throughout processing, including during analogical mapping. Based on the results of Vogel et al. (2005) we anticipated that these ERP results would be modulated by WM span, with high WM span participants showing greater engagement of inhibitory control.

Method

Participants were asked to verify visual analogies constructed from shapes that possessed three varying properties (luminance, orientation, and number; see Figure 1). Before solving each problem, participants were cued to attend to the relation formed by only one of the three

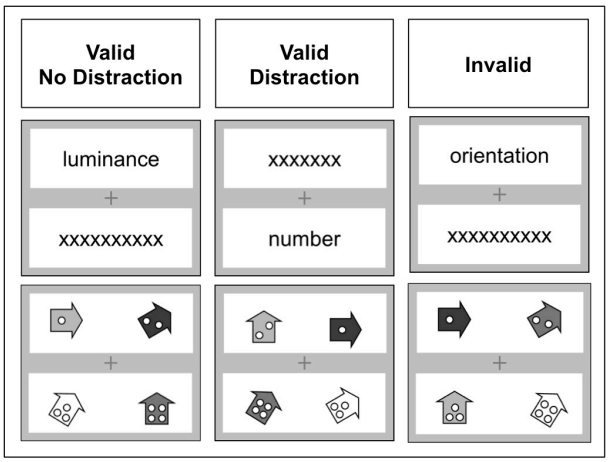

Figure 1: Participants saw analogy problems in one of three conditions. In "Valid–No Distraction" problems, participants mapped based on a single relation for (e.g., luminance—the shapes got darker from left to right), while the other relations (e.g., orientation and number, agreed). In "Valid—Distraction" problems, participants also mapped based on only one relation (e.g., number—the number of dots in the shape decreased from left to right); however, one of the other relations present disagreed with the mapping (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 one of the invalid relations (e.g., orientation—the arrowhead of the shape rotated counterclockwise in the source, but clockwise in the target).

properties (e.g., number). Participants were asked to decide whether the relation in the top pair was the same or different than the relation in the bottom pair (e.g., whether number is increasing from left to right). 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, in spite of the problem requiring a "yes" response. In the "Invalid" condition, the relation of the attended property in the top pair did not match the relation of that in the bottom pair, and thus required a "no" response.

Participants

Seventeen undergraduate students from Loyola University Chicago participated in the experiment. Of the 17 participants, three were omitted from the analysis because of poor EEG recording quality. The other 14 participants were divided into two groups based on their WM span. The low span group (M = 33, SD = 12) had an operation span reliably less than the high span group (M = 57, SD = 5; $t(8.3) = 5.5$, $p = .001$).

Participants gave informed consent to take part in the study and were paid $30 for participation in a 1.5 hour testing session. All procedures were approved by the Loyola University Chicago Institutional Review Board.

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 transitive 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 mismatching relations in only 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 the matching relation 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 mastoid bones for subsequent digital re-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. Raw EEG was re-referenced to an average of the two mastoid electrodes and a 0.01 Hz high-pass filter was applied. 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 ±100μV rejection criterion.

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. The average distance between the participant's head and the monitor was 100cm. 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 jittered fixation screen that lasted 500 to 1000ms. Then, the name of one of the three properties appeared near the fixation point, also for 500 to 1000ms, before it disappeared (for 500 to 1000ms) and was replaced by the stimulus shapes, which remained visible until a button press was made. The entire experiment consisted of 216 trials, and accuracy and response times 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 response times were reported to the participant.

WM Span

After completing the visual analogy task, participants completed a 15-20min 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. The WM span was defined as the total number of letters correctly

remembered in the presented order. Participants were required to perform at a minimum of 85% accuracy in the math problems.

Results

Behavioral Results

Participants maintained above 85% accuracy and had mean response times faster than 2600ms across all three conditions. Because yes-valid/no-invalid responses were used, we report accuracy using d-prime[1] (see Table 1). There was no reliable difference in d-prime between the Valid–No Distraction and Valid–Distraction conditions ($F(1,12) = .022$, *ns*, $\eta_p^2=.002$), no group effect between low and high WM span participants ($F(1,12) = .25$, *ns*, $\eta_p^2=.02$), and no interaction ($F(1,12) = .33$, *ns*, $\eta_p^2=.03$). Participants were slightly faster to make correct Valid-Distractor than Valid-No Distractor verifications ($F(1,12) = 21$, $p = .001$, $\eta_p^2=.6$); however, there were no reliable differences between low and high WM span participants ($F(1,12) = .13$, *ns*, $\eta_p^2=.01$), and no interaction with condition ($F(1,12) = .34$, *ns*, $\eta_p^2=.03$).

Table 1: Behavioral Results.

WM Span	Condition	d-prime	RT (ms) (correct)
Low	Valid-No Distraction	3.5(1.1)	2578(487)
	Valid-Distraction	3.3(1.2)	2188(404)
	Invalid		2504 (439)
High	Valid-No Distraction	3.1(0.8)	2611(288)
	Valid-Distraction	3.2(1.2)	2309(515)
	Invalid		2417 (321)

Error: Standard Deviation

EEG Results

Early N2 ERP Only correct trials in the Valid–No Distraction and Valid–Distraction conditions were used in the neuroimaging analyses. Stimulus-locked event-related potentials (ERPs; see Figure 2), baseline-corrected to 200ms before analogy problem onset were averaged for each condition across all participants. Contrasts between the Valid–No Distraction and Valid–Distraction conditions between 430 and 480ms revealed differences in the N2 ERP, with Valid-Distraction trials showing a more negative N2 relative to Valid-No Distraction trials ($F(1,12) = 5.3$, $p = .04$, $\eta_p^2 =.3$), in electrodes over the left dorsolateral prefrontal cortex. There was no reliable difference between WM groups ($F(1,12) = 1.6$, *ns*, $\eta_p^2 =.1$), and no interaction ($F(1,12) = 1.0$, *ns*, $\eta_p^2 =.08$).

[1] Hit or False Alarm rates of 1 were replaced with .999 and 0 was replaced with .001 for purposes of calculating d-prime.

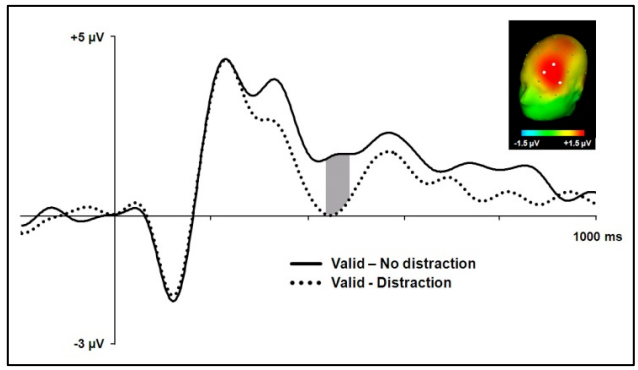

Figure 2: ERPs for correct valid analogies, showing a greater N2 for trials with distraction, recorded in electrodes over left prefrontal cortex. Topographical map shows 430 to 480 ms subtraction.

Late Positive Complex Morrison, Nikitin, and Bharani (2012) used a method previously developed for use with functional magnetic resonance imaging (fMRI; Bunge, Helskog, & Wendelken, 2009), to separate analogical mapping from simple evaluation of perceptual relations. They. identified a frontopolar late positive complex ERP approximately 200 to 600ms prior to response that was strongly correlated with accuracy, which is believed to represent analogical mapping/relational integration. We identified a similar ERP in the present study (see Figure 3) shown here in the stimulus-locked ERPs approximately 1200 to 500 ms prior to response (1000 to 1700 ms after analogy problem onset).

Late Negativity In order to identify whether inhibitory control was operating at a similar time as analogical mapping, we compared ERPs in the 1000 to 1700 post-stimulus range for Valid–No Distraction vs Valid–Distraction conditions for both low and high WM span participants (see Figure 4). Overall there was no effect of distraction ($F(1,12) = 1.7$, *ns*, $\eta_p^2 =.12$); however, there was a difference in the ERPs between the low and high WM

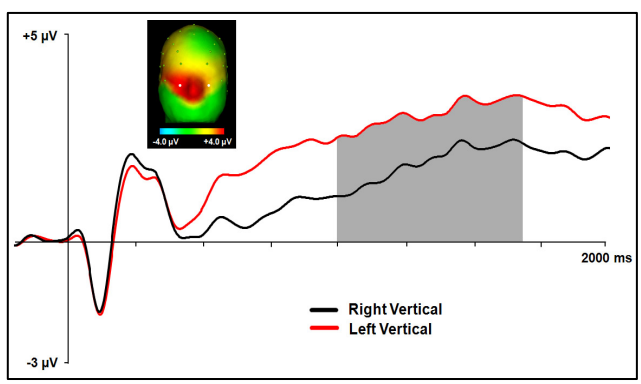

Figure 3: Collapsing across valid analogy problems yielded frontopolar EEG activation patterns very similar to those that have been associated in previous fMRI studies with relational integration during analogical mapping.

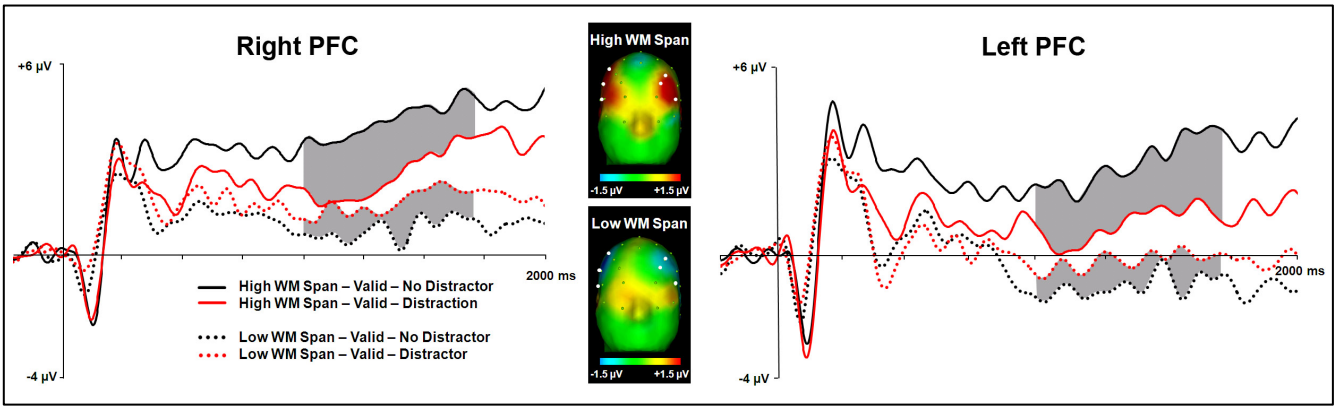

Figure 4: ERPs for High- and Low WM -span participants according to level of distraction in valid trials.

span groups ($F(1,12) = 5.4$, $p = .04$, $\eta_p^2 = .3$) with a reliable interaction between distraction and WM span group ($F(1,12) = 7.1$, $p = .02$, $\eta_p^2 = .37$). Specifically, high WM span participants showed a negativity in the Valid-Distraction condition relative to the Valid-No Distraction condition, while the low WM span participants did not ($F(1,12) = 7.1$, $p = .02$ $\eta_p^2 = .4$)

Discussion

In this study we have for the first time presented evidence that inhibitory control is a central aspect of analogical reasoning both at early and late stages of processing. This result is 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). Although EEG is not well-suited for precise spatial localization, the topography shown in Figure 4 is consistent with the activation reported by Cho and colleagues. It is also interesting that this topography 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 these two areas 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, not in accuracy or RT. It is also interesting that, just as in Vogel et al. (2005), the effective goal-relevant use of inhibitory control interacted with WM span. Specifically, participants with high WM span seemed to show differential activity in bilateral areas of anterior PFC compared to low-WM span individuals. It is not possible with EEG to definitively determine whether this difference involves an increase or decrease of activation in IFG activity in the distraction condition. However, given the similar behavioral performance across the two groups and the previous results from Vogel et al. (2005), it seems possible that this difference may involve IFG-driven suppression mechanisms that are better developed in the high WM group. This ability, while not of behavioral consequence in these simple problems, may manifest itself in better behavioral performance in high WM-span individuals when solving more relationally complex problems.

So what exactly does inhibitory control do during analogical reasoning? It is quite likely that the answer is not a unitary one. Rather, the function of inhibitory control may be multifaceted, and may differ across the time course f processing analogies. Future studies will need to be driven by precise computational accounts of the neural mechanisms underlying analogical processing (e.g., Knowlton et al., 2012) and will likely require time-frequency analysis techniques capable of temporally resolving the interaction between areas in PFC and areas in posterior cortex responsible for the processing of stimuli.

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