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# The Influence of Attentional Selectivity on Insight and Analytic Problem Solving

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ABSTRACT

The Influence of Attentional Selectivity on Insight and Analytic Problem Solving

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Selective attention enables people to focus on a small number of objects, features, or events with good resolution. Sometimes attention may also be *less* selective and distributed across numerous items, which allows more information to be processed at a lower resolution. The degree to which attention is *more* or *less* selective has been linked to analytic and insight problem solving, respectively. In four studies, we examined how manipulating the selectivity of attention in space affects subsequent problem solving and how the selectivity of attention across time may be uniquely related to problem solving tendencies.

In Studies 1 and 2, we investigated how inducing *more* selective attention changes insight and analysis on a verbal problem solving task. In two experiments, we found that people who attended to the global level of hierarchical letter stimuli increased analytic, but not insight, solving compared to baseline. However, attention to the local level of hierarchical letters did not consistently induce more analytic solving across both experiments. Attention to the global letter demands more selective attention because incongruent local letters conflict with the representation of the global letter, which is reflected in larger congruency effects than when attending to the local level (which was indexed by smaller congruency effects). Thus, in a third experiment, we manipulated the saliency of the global level of information, which changes the amount of conflict inherently present within the global letter, to increase or decrease the relative amount of selective attention required for the task. People who attended to global letters that were locally-salient (i.e., the identities of incompatible local letters strongly interfered with the

global letter) demonstrated larger congruency effects and subsequently increased analytic solving compared to baseline. Additionally, people with less selective attention (i.e., indexed by larger congruency effects, reflecting a poorer ability to selectively attend to conflicting information in general) tended to solve more verbal problems with insight at baseline whereas people with more selective attention tended to solve more verbal problems with analysis at baseline.

In Study 3, we investigated how inducing *less* selective attention changes insight and analytic problem solving. We found that people who performed an ensemble statistics task that required distributed attention also subsequently solved more verbal problems with insight than at baseline. However, people who performed a version of the ensemble statistics task in which they judged the size of a single circle, which may have required more selective attention, did not subsequently change in either insight or analytic problem solving.

And finally, in Study 4, we explored how individual differences in attentional blinks are related to the tendency to solve problems with insight or analysis. Some people, known as nonblinkers, can avoid attentional blinks by allotting less attention to irrelevant distractors while other people, known as blinkers, invest too much attention on these distractors and demonstrate deep attentional blinks. Correlations between the magnitude of the attentional blink and problem solving were not reliable, but there was a negative trend between attentional blink magnitudes and insight solving and a positive trend between attentional blink magnitudes and analytic solving. Nonblinkers reliably solved more problems with insight than analysis in general, but blinkers did not solve reliably more problems with either solving process. Nonblinkers also tended to solve more problems with insight than blinkers, while blinkers tended to solve more problems with analysis than nonblinkers, but these findings were only marginally reliable.

The findings from our study extend the literature on the role of attention in problem solving processes. Modulating visual attention appears to influence conceptual attention, which, in turn, biases insight or analytic problem solving. Specifically, less selective or more distributed attention is conducive to subsequent insight problem solving whereas more selective attention facilitates analytic solving.

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## 1.1 Introduction

Sometimes, people can solve problems analytically by working consciously, deliberately, and continuously. Other times, however, people may experience a sudden shift in their interpretation of the problem space and arrive at a correct and non-dominant solution spontaneously. This latter phenomenon is known as insight, and it is often accompanied by positive feelings of surprise and confidence that the solution is correct (for a review, see Kounios & Beeman, 2014). Prior to an insight experience, a person could have also encountered a mental block or impasse during which they were fixated on a dominant but ultimately incorrect solution. Insight is associated with unique phenomenological experiences, neural correlates, and attentional states prior to encountering the problem (i.e., at preparation) and during solution (e.g., Jung-Beeman et al., 2004; Kounios et al., 2006; Metcalfe & Wiebe, 1987).

High-level cognitive processes like problem solving involve interactions between several brain networks including those involved in cognitive control and attention. Here, we will specifically examine the interplay between insight problem solving and attention. Attention selectively filters information that is relevant to our current tasks and goals from competing irrelevant information. At any given time, people can attend to only a small amount of information from our external or internal worlds (e.g., Desimone & Duncan, 1995). However, people can attend to varying amounts of information with certain costs and benefits, depending on the degree of attentional selectivity (see Figure 1, reprinted from Alvarez, 2011). When people are engaged in selective (or focal) attention, they can process small amounts of information with high resolution. At the same time, they must protect their selected information from interference by ignoring other information. People who are engaged in less selective (or more distributed) attention, however, may take in more information (i.e., filtering less information), or distribute their attention across multiple objects or features, at the cost of processing that information at a lower resolution (e.g., Treisman, 2006).

People can deploy more or less selective attention to information within either their external or internal worlds. Specifically, people may attend to different features (e.g., color, shape, or tones) or objects within different sensory modalities (e.g., vision and audition) in the external world. Additionally, people may pay attention to visual features not only within visual space (i.e., spatial attention) but also over moments in time (i.e., temporal attention). Finally, people also attend to their internal trains of thoughts, such as cognitive representations, while suppressing input from the external world (for a review, see Chun, Golomb, & Turk-Browne, 2011).

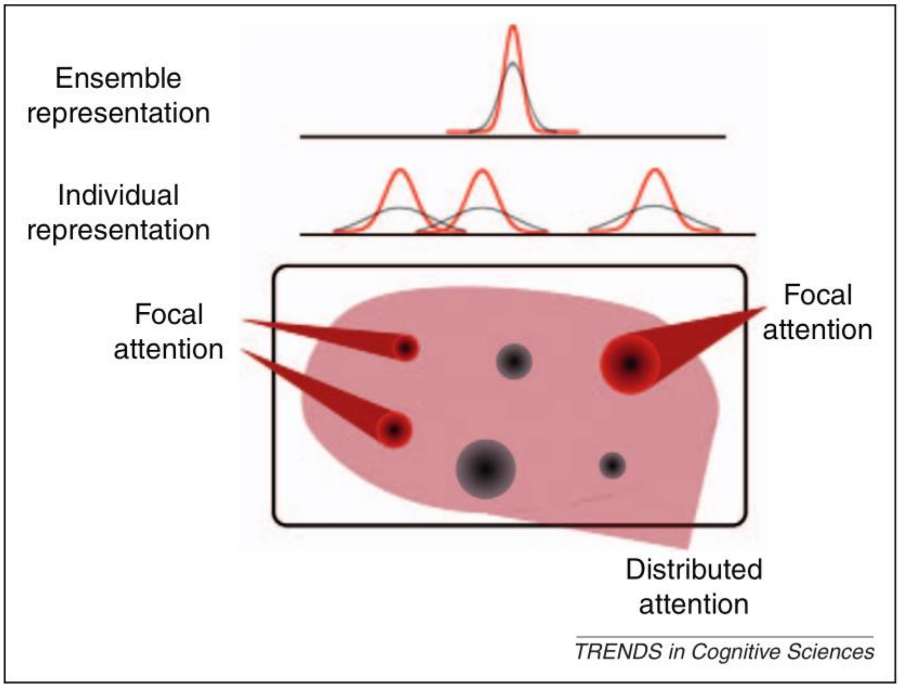


*Figure 1.* A comparison of focal (more selective) and distributed (less selective) attention.

This schematic demonstrates how attention can be selectively focused on individual objects or features, as represented by "focal attention" spotlights, which would enable processing small amounts of information with high resolution. Conversely, attention can be diffusely distributed across several objects or features, which would allow processing more information but at the cost of lower resolution. The gray curves represent diffusely attended representations whereas red curves represent focally attended representations, which are more precise for individual representations. The curves demonstrate the power of distributed attention in representing average information as the mean of all individual representations (top gray curve) is rather precise for ensemble representations. Reprinted from "Representing multiple objects as an ensemble enhances visual cognition", by Alvarez, G. A., 2011, *Trends in Cognitive Sciences*, *15*(3), p. 124. Copyright 2011 by Elsevier. Adapted with permission.

## 1.2 Direct Connections Between Visual Attention, Conceptual Attention, and Problem Solving Processes

When people attempt to solve problems, they could selectively attend to a particular internal representation (i.e., conceptual attention), such as a dominant association between two or more concepts, while ignoring other representations. Alternatively, their attention may be less selective and distributed across remotely associated concepts, which may encourage the selection of weaker internal representations. Some studies have modulated the selectivity of conceptual attention using overinclusive thinking tasks that ask people to associate concepts from distantly-related categories (e.g., Chiu, 2015; Chrysikou, 2006; Wen, Butler, & Koutstaal, 2013), which weakens category boundaries and facilitates connections between remote associations. Moreover, when people reduce the selectivity of their conceptual attention, they induce an attentional state conducive to insight solving. For example, people who decreased the selectivity of their conceptual attention by providing alternative categories to which a common object may belong (i.e., broadened conceptual categories) solved more insight problems than people who performed a word association task or an embedded figures task (Chrysikou, 2006). In a similar study, people who came up with alternative uses for common objects, thereby reducing the selectivity of their conceptual attention, solved more insight problems compared to those who performed a word association task or no intervening tasks (Wen, Butler, & Koutstaal, 2013). Finally, people who categorized exemplars from distant semantic categories, thus decreasing the selectivity of their conceptual attention, solved more classic insight problems than people who categorized exemplars into their most common category (Chiu, 2015).

Selective attention to external stimuli within a sensory modality (e.g., visual or auditory) can modulate the selectivity of conceptual attention, which can subsequently bias how people ultimately solve problems, whether by insight or analysis. Evidence from individual differences literature show that less selective attention is related to insight, whereas more selective attention is related to analysis. For example, in a study by Mendelsohn & Griswold (1964), people memorized a list of words (i.e., “focal” list) while a second list of words that was to be ignored played in the background (i.e., “peripheral” list). Both focal and peripheral word lists covertly contained solutions to anagrams they would later solve and would serve as an index of selective attention. People who solved more Remote Associates Test (RAT) problems, which are typically solved with insight (e.g., Webb, Little, & Cropper, 2017), also solved more anagrams whose solutions were embedded in the focal list of words. Additionally, these same “high insight” people solved more anagrams whose solutions were embedded in the peripheral list. A more recent replication of the Mendelsohn and Griswold (1964) study demonstrating that differences in problem solving tendencies can be explained by individual differences in selective attention. People who were more susceptible to task-irrelevant auditory stimuli (i.e., had less selective attention) tended to solve more Remote Associates Test (RAT) problems typically solved with insight with no effect on analytic solving (Ansburg & Hill, 2003). That is, people with less selective attention were better insight solvers and were not just better problem solvers (as there was no difference in analytic problem solving). Conversely, a greater ability to ignore irrelevant distractions, or having more selective attention as indexed by higher working memory capacity, is associated with better performance on analytic problems (Wiley & Jarosz, 2012).

Directly modulating the selectivity of attention within a sensory modality also influences the selectivity of conceptual attention and subsequent problem solving. One study examined how inducing either a more or less selective attentional state through visual attention tasks changes analytic versus insight solving, as indexed by Compound Remote Associates (CRA) Problems (Wegbreit, Suzuki, Grabowecky, Kounios, & Beeman, 2012). People solved more CRA problems with analysis after performing a central flanker task that putatively demanded more selective attention, thereby enhancing distractor-filtering and inducing an attentional state conducive to analytic solving. Conversely, people solved more CRA problems with insight after performing a Rapid Object Identification task that putatively demanded less selective or more distributed attention, thus inducing an attentional state that facilitates the detection of weakly activated semantic associations conducive to insight solving. Alternatively, detecting weakly activated representations of objects may modulate the threshold for detecting other weak representations, such as remote associations, required for insight solving.

Another study reported similar findings using different visual attention tasks: People solve more classic insight problems with insight when they are induced into a less selective attentional state that encourages the detection of weakly activated and non-dominant solutions (Laukkonen & Tangen, 2017). People observed either a Necker Cube, a bi-stable image that often “flips” perspectives, or two static and alternating views of the Necker Cube, and then attempted traditional insight and analytic problems. The authors suggested that resolving the conflicting bi-stable perspectives of Necker cubes may activate conflict monitoring areas (Laukkonen & Tangen, 2017). These conflict monitoring areas include some areas of the anterior cingulate cortex (ACC) that are more active during solutions with insight (compared to non-insight or analysis) and during preparatory brain states conducive to subsequent solutions with insight (e.g., Kounios et al., 2006). Other studies posit that activation of the ACC may promote the detection of weakly activated associations, perhaps by reducing cognitive control and increasing cognitive flexibility (Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009). People who observed the Necker cubes solved more traditional insight problems correctly and were more likely to report solving those problems with insight. On the other hand, people who viewed the static and alternating perspectives reported more analytic or “other” solutions for these insight problems. Thus, attending to multiple perspectives of an ambiguous visual image might increase cognitive flexibility (perhaps as a consequence of resolving said conflict, which activates the ACC to reduce cognitive control), which may subsequently induce less selective conceptual attention that is conducive to insight solving.

### 1.3 Indirect Connections Between Visual Attention, Conceptual Attention, and Problem Solving Processes

Several lines of research have investigated how modulating a third variable, such as mood or executive control, indirectly affects attentional selectivity and, in turn, influences problem solving processes. For example, people who are induced into a positive mood tend to solve more problems with insight but not analysis. Additionally, weakening executive control benefits insight, but strengthening executive control improves analysis. The literature suggests that an underlying domain-general attentional mechanism (i.e., the selectivity or distribution of attention) may explain the link between a third variable, like mood or executive control, and problem solving processes.

In general, positive mood, whether it is induced tonically (i.e., lasting an entire test session) or phasically (i.e., lasting a single trial), tends to facilitate insight problem solving. In a seminal experiment, people who were induced into a positive mood through comedic film clips or an unexpected gift were more likely to solve the Duncker Candle Task (i.e., a classic insight problem) and solved more Remote Associate Test (RAT; i.e., typically solved with insight) problems than people in either neutral or negative moods (Isen, Daubman, & Nowicki, 1987). People correctly solved more positively-valanced RAT problems (i.e., a phasic mood induction) than negatively-valanced RAT problems. Moreover, people solved more neutral RAT problems preceded by a consonant chord (i.e., a phasic positive affect manipulation) than RAT problems preceded by discordant musical clips (i.e., a phasic negative affect manipulation; Topolinski & Deutsch, 2012).

Positive mood may facilitate insight solving by modulating attention, and this modulation may subsequently bias problem solving processes. Positive mood has been associated with less selective visual attention (for a review, see Vanlessen, De Raedt, Koster, & Pourtois, 2016). For example, people in a positive mood demonstrate reduced selective visual attention to simple perceptual features (i.e., direction of motion) compared to people in neutral and sad moods (Uddenberg & Shim, 2015). Additionally, people in a positive mood are more distractible, which decreases the selectivity of attention and may inadvertently allow irrelevant information to be processed (Biss & Hasher, 2011). At the same time, the increase in distractibility and reduction in selectivity of attention may also increase the likelihood of weakly-activated information reaching awareness when it becomes relevant in subsequent problem solving tasks, thereby benefitting solving performance.

Rowe, Hirsh, and Anderson (2007) attempted to directly bridge the relationship between mood, attention, and problem solving. People were induced into positive, sad, or neutral moods and performed the Eriksen Flanker Task (i.e., a visual attention task that indexes attentional selectivity) and attempted to solve RAT problems (i.e., a measure of semantic breadth and insight solving). People solved more RAT problems and were more likely to process flankers spaced far apart from the central target when they were induced into a positive mood versus neutral or sad moods. These findings suggest that positive mood reduces the selectivity of both visual (i.e., far-flankers were less likely to be suppressed) and conceptual attention, which is conducive to insight solving.

Moreover, moods differentially modulate neural activity involved in insight and non-insight problem solving, and these mood effects may be explained by changes in executive control and attention (Subramaniam, et al., 2009). People who reported being in a positive mood (at baseline) solved more CRA problems and reported solving more problems with insight compared to people who were anxious. These findings were replicated when people were induced into either positive, anxious, or neutral moods using film clips (Subramaniam, 2008). People in a positive mood showed increased neural activity in parts of the anterior cingulate cortex (ACC), which includes areas involved in conflict monitoring and cognitive control, prior to the presentation of CRAs later solved with insight and during insight solution (Subramaniam et al., 2009). The results of these two studies suggest that positive mood may influence subsequent problem solving by modulating cognitive control and conflict monitoring (i.e., executive control functions) through ACC activity, which is corroborated by other studies investigating the relationship between positive mood and cognitive control (for a review, see

Chiew & Braver, 2011). Particularly, positive affect reduces cognitive control, which increases cognitive flexibility (i.e., the ability to quickly switch attention between different stimuli or goals) and reduces perseveration at the cost of increased distractibility (Dreisbach & Goschke, 2004; Heerebout, Todorović, Smedinga, & Phaf, 2013), possibly through modulation of the dorsal ACC (Wang, Chen, & Yue, 2017) and the posterior cingulate cortex (PCC) (Braem et al., 2013). The PCC has strong connections to the ACC, appears to be important in detecting environmental changes (which then encourages behavioral changes), and may play a pivotal role in controlling the selectivity or distribution of attention (Leech & Sharp, 2014; Pearson, Heilbronner, Barack, Hayden, & Platt, 2011). Although Subramaniam and colleagues (2009) did not find a reliable correlation between positive mood, insight, and PCC activity, they found that higher PCC activity at preparation was related to higher subsequent insight solving, which was also found in other studies comparing insight to non-insight solutions at preparation (Kounios et al., 2006). In summary, positive affect modulates cognitive control and reduces the selectivity of attention, which enhances the detection and use of weakly-activated information that may have been otherwise suppressed.

An examination of the relationship between executive control of attention (also known as cognitive control) and problem solving processes also reveals an underlying attentional link. People engage in executive control to maintain task goals, such as when selectively attending to some stimuli while ignoring irrelevant information (e.g., Niendam et al., 2012), which activates the "executive control network". This network includes the dorsolateral prefrontal cortex and posterior parietal cortex (e.g., Niendam et al., 2012; Seeley et al., 2007). A related network of brain areas known as the "salience network" is activated when people detect conflict (i.e., conflict monitoring), such as when overcoming dominant but incorrect responses during problem solving. The “salience network” is comprised of parts of the anterior cingulate cortex and insula (for a review, see Botvinick, Cohen, & Carter, 2004), including areas that are often implicated in insight solving (e.g., Kounios et al., 2006; Subramaniam et al., 2009). Conflict monitoring and executive control may interact when people detect a conflict (e.g., a dominant but incorrect solution), which co-activates the salience and executive control networks and subsequently modulates top-down control and attentional selectivity (e.g., Botvinick, Braver, Barch, Carter, & Cohen, 2001; Botvinick et al., 2004). This interaction may occur when people solve problems, as suggested by the faciliatory relationship between positive mood and insight solving. Specifically, positive mood may modulate ACC activity, facilitating the detection of non-prepotent or non-dominant responses (Chiew & Braver, 2011) and reducing executive control (for a review, see Mitchell & Phillips, 2007), which may subsequently reduce attentional selectivity in a way that is conducive for insight solving.

Several studies have linked reduced executive control of attention, as measured by inhibitory control and working memory capacity tasks, with increased insight solving. People who demonstrated larger Stroop effects, which illustrates poorer inhibitory control, also tended to solve more Rebus Puzzles (Tidikis & Ash, 2018), which are often solved with insight (e.g., Threadgold, Marsh, & Ball, 2018). Conversely, people with a higher degree of reported self-control tended to solve more verbal problems with analysis (Hechtman, 2015). In addition, people with higher working memory capacity, an index of (better) attentional control, and more baseball knowledge tended to fixate on incorrect and misleading solutions to baseball-related RAT problems compared to people with lower working memory capacity and the same level of baseball knowledge (Ricks, Turley-Ames, & Wiley, 2007). Thus, this study suggests that greater attentional control may be related to increased selective attention to dominant but incorrect solutions.

People tend to solve more problems with insight after relaxing executive control, which could be explained by a decrease in attentional selectivity. For example, moderately intoxicated people did not improve their performance on an operation span task (i.e., a measure of working memory capacity and executive control) after consuming alcohol, but sober people improved on this task over time. Moderately intoxicated people also solved more RAT problems and reported solving them by insight more often than sober people (Jarosz, Colflesh, & Wiley, 2012). A recent study replicated the findings of Jarosz, again linking mild alcohol intoxication with both improved RAT performance and reduced executive control (Benedek, Panzierer, Jauk, & Neubauer, 2017). Specifically, only sober people, but not mildly intoxicated people, performed better on a verbal 2-back task at retest than at baseline, which suggests that alcohol consumption reduced executive control. At the same time, mildly intoxicated people solved more RAT problems than sober people, indicating better insight solving. Although these studies did not measure all aspects of executive control, other studies report that alcohol intoxication reduces intentional inhibitory control of attention and disrupts early sensory gating as measured by P50 and N100 (Abroms, Gottlob, & Fillmore, 2006; Sklar & Nixon, 2014). In other words, alcohol consumption can impair selective attention or the ability to filter irrelevant information, resulting in less selective or more distributed attention. Thus, mild or moderate alcohol consumption facilitates insight solving, most likely by reducing executive or inhibitory control and decreasing attentional selectivity.

Older adults tend to have reduced executive control, which results in increased distractibility and less selective attention (i.e., poorer filtering of irrelevant information). This increased distractibility may be beneficial when solving insight problems but is disadvantageous when the intruding information is irrelevant (Kim, Hasher, & Zacks, 2007). Additionally, people tend to have reduced executive control during their non-optimal times of the day, which also benefits insight solving: Younger adults solved more insight problems during their non-optimal times of day than those tested during optimal periods (Wieth & Zacks, 2011). Older adults with reduced executive control showed an even larger benefit for insight solving than younger adults when tested during non-optimal times of day (May, 1999).

Certain types of meditation practice, particularly open monitoring (OM) meditation, have also been linked to insight and analytic problem solving. Meditation practitioners solved more CRA problems with insight after a session of OM meditation, but did not increase insight nor analytic solving after a session of focused attention (FA) meditation. (Colzato, Szapora, Lippelt, & Hommel, 2017). Another study found that novices solved more Chinese CRA problems after being trained in integrative mind-body meditation, which is similar to OM meditation (Ren et al., 2011). In addition, people trained in integrative mind-body meditation also demonstrated greater activity in the MFG and IFG during insight. Increased IFG activity is linked to the ability to inhibit prepotent responses, which may also play a role in insight solving such as that ability to inhibit a dominant but ultimately incorrect solution in favor of a less salient solution. OM meditation is also associated with improvements on most attention tasks including attentional flexibility (e.g., Ainsworth, Eddershaw, Meron, Baldwin, & Garner, 2013). Additionally, in OM meditation, one does not selectively attend to any object, feeling or thought (Lutz, Slagter, Dunne, & Davidson, 2008), so it is possible that the ability to engage in this distributed form of attention could also be beneficial for insight solving.

Finally, people who were more likely to mind wander, a sign of reduced executive control and less selective attention (e.g., Handy & Kam, 2015; McVay & Kane, 2010), were also more likely to solve CRA problems with insight (Zedelius & Schooler, 2015) and discover a hidden rule during a Number Reduction Task (i.e., usually by insight; Tan, Zou, Chen, & Luo, 2015). Conversely, people who were less likely to mind wander (i.e., stronger executive control) tended to solve CRA problems analytically (Zedelius & Schooler, 2015). A study by Leszczynski and colleagues (2017) more directly linked deficits in attention during mind wandering with benefits in subsequent insight problem solving. Here, the authors asked people to perform a sustained attention task (SART) during an incubation period (i.e., time spent away from unsolved problems) for unsolved CRA problems. The SART served as a method to cue problem words from the unsolved CRAs and as a measure of mind wandering. People who demonstrated more mind wandering during the incubation period (when unsolved problem words were also cued) also tended to solve more CRA problems after the incubation period (Leszczynski et al., 2017). People who mind wandered more often also demonstrated slower and more variable reaction times during the SART, which suggests that attention was disengaged from sensory input during mind wandering and turned inward, perhaps toward internal representations of semantic associations stimulated by the cued problem words. In addition, the tendency to mind wander more often is associated with poorer attentional control (Unsworth & McMillan, 2014), which may suggest that attention in these individuals tends to be more distributed or less selective.

**1.4 Summary and Overview of Studies**

Insight and analytic problem solving processes appear related to different degrees of attentional selectivity in both perceptual and conceptual domains. Specifically, attention that is less selective or more distributed, both perceptually and conceptually, is relatively conducive to insight solving. Here, we defined “less selective” or “distributed” attention as the ability to attend to multiple objects, features, or events, perhaps at a lower resolution than when attention is selective. Conversely, attention that is more selective is relatively conducive to analytic solving. We defined “more selective attention” as the ability to focus attention on an object, feature, or event while ignoring other objects, features or events.

Findings from the positive mood literature also suggest that attention and executive control may interact to produce an attentional state that may facilitate either insight or analytic solving. Particularly, positive mood may facilitate insight solving by modulating conflict monitoring and weakening executive or inhibitory control, which subsequently reduces attentional selectivity and increases the likelihood that weakly-activated representations are selected. Executive control can be reduced by becoming moderately intoxicated, during mind wandering or non-optimal times of day, or as a natural consequence of aging. People with reduced executive or inhibitory control of attention may also have less selective attention as a result of a decreased ability to filter irrelevant information, which is conducive to insight problem solving.

Although a few studies have tentatively shown that modulating perceptual and conceptual attention shifts how people solve problems, there are still several open questions regarding the precise relationship between selectivity and solving processes. The following chapters report three studies investigating how attending to one level of a local-global hierarchical display modulates attention for problem solving, one study that investigates how performing ensemble statistics tasks modulate the selectivity of attention and affect subsequent problem solving, and an individual differences study that investigates how the ability to distribute attention over time is related to problem solving.

Some research associates a bias for “global attention”, or a tendency to more quickly respond to or detect holistic information, with increases in some aspects of creativity (e.g., Zmigrod, Zmigrod, & Hommel, 2015). However, the visual tasks typically used to index “global attention” typically require the viewer to attend to information at one level while suppressing information at the other competing level. Thus, global-local visual attention tasks may not “broaden” or “diffuse” attention as one might expect, but they may instead demand selective attention, which should induce an attentional state conducive to analytic rather than insight solving. Indeed, in three studies (Chapter 2), we demonstrate that people who made judgments at the global level in a modified version of the Navon letter task (Navon, 1977) had more selective visual attention and subsequently solved more verbal problems analytically.

Extending the findings from Chapter 2, we also sought to modulate attention through visual attention tasks that putatively demand more distributed (or less selective) attention in Chapter 3. Additionally, given the dearth of attentional manipulations on problem solving, it is unclear whether domain-general attentional manipulations facilitate insight solving, or if specific components are required. For example, the rapid object identification task involves a semantic component, which may bridge the relationship between visual and conceptual attention to promote attention to weakly activated representations. Using a visual attention task that does not contain a semantic component but can also induce less selective attention, such as an ensemble statistics task, should help disentangle this issue. If *more selective* attention facilitates analytic solving, we expected that *less selective* or *more distributed* attention should facilitate insight solving. Indeed, we found that people solved more verbal problems with insight, but did not change in analytic solving, after they performed an ensemble statistics task that required distributed attention.

Finally, studies investigating attention related to problem solving generally occur within a spatial domain, which obscures the domain-generality of these attentional mechanisms. In Chapter 4, we investigated non-spatial attentional selectivity with a temporal attention phenomenon known as attentional blink (AB), which should help elucidate whether the attentional mechanisms underlying problem solving processes is indeed domain-general. An AB describes a phenomenon in which people are unable to report (i.e., "blink") the second of two targets embedded within a stream of rapidly and serially presented distractors, particularly when the second target appears in close temporal proximity to the first. However, some people known as "nonblinkers" do not demonstrate this decrement in performance. The ability to avoid or suppress an AB may be attributed to an enhanced ability to allocate or distribute attention, which results in a less selective attentional state conducive to this visual attention task and that may also be conducive to insight solving. In an exploratory study, we correlated AB magnitude, a putative index of how well people can allocate their attention across temporal events, with problem solving performance. While our correlations were not statistically reliable, we did observe a weak negative relationship between AB magnitude and insight solutions and a weak positive relationship between AB magnitude and analytic solutions. In addition, when we examined the problem solving performance of people in the top and bottom quartiles of AB magnitudes (i.e., “deep blinkers”, or people who show a robust AB, and nonblinkers, respectively), we found that 1) nonblinkers solved reliably more problems with insight than with analysis; 2) nonblinkers solved more problems with insight than blinkers, but this result was marginally reliable; and 3) blinkers solved more problems with analysis than nonblinkers, though again this result was only marginally reliable.

# Chapter 2: Selective Attention to Global Stimuli Induces Analytic Problem Solving

## 2.1 Study 1a: Experiments 1 and 2

People can solve problems several ways, and their success and manner of solving varies with their current state of attention. Often, people solve problems analytically – employing strategies, advancing step-by-step, or perhaps in combination with a trial-and-error approach. Even straightforward analytic approaches can sometimes yield solutions that seem creative. Some analytic approaches can be intentionally creative, such as deliberately approaching a problem from an alternative angle. Other times, solutions can precipitate suddenly and unexpectedly as a phenomenologically and neutrally distinct process compared to the solving strategies previously employed. These solutions are known as insights or “Aha!” moments, which typically involves unconscious processing. Insight often leads to creative solutions, and is it considered by many to be a creative process (for review, Kounios & Beeman, 2014; Sternberg & Davidson, 1995).

Visual and conceptual attention influence how we ultimately solve a problem (e.g., Rowe et al., 2007; Wegbreit et al., 2012). There are two competing interpretations regarding how different attentional states are conducive to either analytic and insight problem solving: One idea is that narrowed attention (both visuospatial and conceptual) is more conducive to analytic solving, whereas broadened attention is conducive to insight and creative thinking. “Broadened attention” may be meant rather literally in that attention is spatially broadened over visual space and broadened over “conceptual space” (e.g., Rowe et al., 2007). Another idea is that *more selective* attention – that is, increased attentional filtering to decrease conflict or competition between two or more stimuli – is conducive to analytic problem solving. Conversely, *less* *selective* or *more distributed* attention, which allows multiple stimuli or features to be processed (perhaps with less depth or at a lower resolution), is conducive to insight solving and creativity.

Support for the idea that broadened visuospatial attention is conducive to insight solving comes from one study that examined the parallel effects of mood on both attention and insight solving. People listened to mood-inducing music, performed a visual flanker task to index visual attention, and then solved Remote Associates Test (RAT) problems – a putative index of creative cognition and a measure of insight solving (Rowe et al., 2007). When people were induced into a positive mood (compared to when they were induced into neutral or sad moods), they experienced interference when responding to central letters with incompatible flanking letters that were spaced far apart, which indicated that attention was spatially broadened. At the same time, people in a positive mood solved more RAT problems than when they were in either neutral or sad moods. These findings suggest that positive mood may facilitate insight solving by broadening visuospatial (and subsequently conceptual) attention. Specifically, detecting weak semantic features or associations requires broadened conceptual attention, which may be linked to broadened visual attention.

Another possibility is that positive mood decreases attentional ***selectivity*** in visual processing and in semantic search during problem solving. This reinterpretation is consistent with the idea that insight often arises after reaching a mental impasse, which could occur when people selectively attend to a dominant but ultimately incorrect solution. People may be able to overcome the impasse by reducing their selectivity to enhance access to non-dominant associations (for review, Kounios & Beeman, 2014; Sandkühler & Bhattacharya, 2008).

Cross-task correlations demonstrate that individual differences in selective attention relate to insight and analytic problem solving differently (Ansburg & Hill, 2003). People who solved more RAT problems (i.e., high-insight solvers), compared to their analytic counterparts, were more influenced by peripheral cues on a separate anagram task. Specifically, the high-insight solvers were more distractible, which was demonstrated by greater intrusion of peripheral items they were supposed to ignore. Thus, less selective attention was associated with better insight solving as defined by more RAT solutions (Ansburg & Hill, 2003). Additional support for this interpretation comes from EEG patterns related to individual differences in solving (Kounios et al., 2008). People who tended to solve problems by insight showed less occipital alpha-band activity at rest than analytical solvers, suggesting that insight solvers generally have less selective attention. In contrast, people who tended to solve anagrams analytically showed greater occipital beta activity at rest, suggesting that analytic solvers generally engage in more selective attention (Kounios et al., 2008).

If selective attention underlies problem solving, does modulating the selectivity of attention influence subsequent problem solving? At least one study directly manipulated attention with tasks that putatively modulate selectivity, which then affected problem solving in a manner consistent with the individual differences literature. People solved more Compound Remote Associate (CRA) problems with insight after performing a rapid object identification task that provided insufficient perceptual input to select an interpretation of the object, thus encouraging them to decrease the selectivity of their attention (Wegbreit et al., 2012). In contrast, people solved more CRA problems analytically after performing a visual flanker task that requires selective attention. When performing the flanker task, people generally respond more slowly on trials with incongruent information (i.e., the target and flanking letters are mismatched, causing a response conflict) compared to trials with congruent information (i.e., the response is the same when the target and flanking letters match; e.g., Casey et al., 2000). This difference in latency, known as a congruency effect, provides an index of how quickly people can filter competing information and allows us to directly examine the degree of attentional selectivity.

Given that modulating attention with visual tasks can influence problem solving, is there a visual attention task that can test the competing interpretations of how attention affects problem solving? Navon letters (Navon, 1977) – hierarchical letter stimuli consisting of a large “global” letter made of smaller “local” letters – may be an ideal candidate for this investigation. Navon letters contain both a broad spatial display and conflicting information at both levels (i.e., when the global and local letters are mismatched). Traditionally, Navon letters have been used to investigate local and global processing in visual scenes, which generally contain multiple levels of information. For example, in a scene of a forest containing many trees, we may “see the trees” when we process local features or “see the forest” when processing global features. The hierarchical letter task is also interesting because a focus on the global level of information has been associated with right hemisphere advantages in studies with patients (Robertson & Lamb, 1991), in neuroimaging studies (Fink, Marshall, Halligan, & Dolan, 1998; Martinez et al., 1997), and in divided visual fields studies (Lux et al., 2004), and it benefits from positive mood (Basso, Schefft, Ris, & Dember, 1996; Fredrickson & Branigan, 2005). Similarly, insight has been associated with right hemisphere processing (Beeman & Bowden, 2000; Bowden & Beeman, 1998; Bowden & Jung-Beeman, 2003a) and positive mood (Subramaniam et al., 2009). While there may be good reasons for these parallels, these are also distinct domains with disparate neural substrates.

Given the multiple cross-domain parallels, we tested the competing hypotheses about attentional breadth versus selectivity in the context of global versus local processing of hierarchical stimuli. In the following two experiments, participants solved CRA problems before and after making judgments about the identity of letters at the Local level, at the Global level, or Matching across levels. For each CRA problem, participants simultaneously saw three problem words (e.g., PINE—CRAB—SAUCE) and looked for a solution word (e.g., APPLE) that could form a common two-word phrase with all three problem words (e.g., PINEAPPLE, CRAB APPLE, and APPLE SAUCE; Bowden & Jung-Beeman, 2003b). Participants reported whether they solved each problem with analysis or sudden insight, allowing us to study solution type without confounding problem type (e.g., Bowden, Jung-Beeman, Fleck, & Kounios, 2005; Jung-Beeman et al., 2004; for review, Kounios & Beeman, 2014). The main experimental question was whether and how the visual attention task (i.e., the local-global letter task) would change problem solving.

Whether the critical feature of attention is spatial extent or selectivity, we predicted that attending to the Local level of the hierarchical letters should induce more analytic solving. Local visual processing could require spatially narrow attention and a focus on small details while ignoring the bigger picture (e.g., Cohen, 2014), which should be conducive to analytic solving if it also narrows the scope of attention at the conceptual level. At the same time, it is equally plausible that local processing encourages selectivity; that is, when processing local features, one must selectively attend to the local feature while suppressing interference from the global level.

However, the prediction remains the same: If attention to the Local level increases the selectivity of attention, people should solve more problems analytically, which should be inversely related to the magnitude of congruency effects (i.e., because stronger selection would decrease the congruency effect) in the visual attention task.

Two competing predictions can be made regarding how attention to the Global level of hierarchical letters will affect problem solving. If global processing engenders generally broadened attention (i.e., spatially for visual information and conceptually for verbal problems), then people will have broadened visual attention after responding to the Global level. If the attention mechanism is general, they should also broaden conceptual attention and solve more problems with insight. A contrasting prediction for the Global task hinges on the selectivity of attention. Responding to the Global level, regardless of information at the Local level, attention to the Global level should encourage increased selectivity as much as, if not more than, attention to the Local level. If the key dimension of attention underlying insight versus analytic solving is the degree of selectivity, then people responding to the Global stimuli should show at least as large of a congruency effect as those who responded to Local stimuli in the visual attention task, and they should solve more problems analytically.

We calculated congruency effects, a measure of attentional selectivity, by comparing latencies in incongruent versus congruent trials in both Local and Global versions of the visual attention task. In a separate exploratory analysis, we examined the relationship between individual differences in selective attention (indexed by congruency effects) and problem solving preferences (i.e., tendency to solve problems with insight or analysis). Particularly, smaller congruency effects should be associated with more analytic solving, and larger congruency effects should be associated with more insight solving.

If less attentional selection is required for insight solving, then perhaps we can encourage participants to attend to both levels of hierarchical information simultaneously without selecting one over the other. Thus, we created a third version of the attention task – the Match version – in which participants match targets across local and global levels, which should decrease attentional selectivity and be conducive to insight solving. Unfortunately, the Match task does not provide a measure of congruency to index selectivity because congruency is the basis of their decision; that is, participants respond differently to the congruent (yes) and incongruent (no) trials. Matching across local and global levels may, however, require people to rapidly switch their attention between both levels. Some evidence suggests that the ability to switch attention quickly (i.e., flexible attention) involves selective attention (Zabelina, Saporta, & Beeman, 2016). Thus, if the Match task enhances rapidly switching attention between two levels and requires selective attention, participants should subsequently solve more problems analytically.

### 2.1.1 Study 1a Methods

**Participants.** Seventy eight undergraduate students (41 females, mean age = 18.8 years) participated in Experiment 1 for partial course credit. We also excluded data from two participants whose CRA solving performance was below 61.29% (see related outlier analysis). We excluded data from five participants (which includes the two participants whose solving performances were considered outliers) who did not use the insight or analytic ratings, ultimately analyzing data from 73 participants (39 females, mean age = 18.8 years).

In total, 115 participants were recruited to participate in this study. One hundred and one undergraduate students (59 females, average age = 18.7 years) participated in Experiment 2 for partial course credit. Fourteen undergraduate students (9 females, mean age = 20.9 years) were paid $10 for their participation in Experiment 2. Data from six participants were excluded from further analyses for not using the insight or analytic ratings. Data from three participants were excluded due to poor solving performance on the CRA task (see related outlier analysis). We also excluded five participants with whose performance fell below 63.34% on the first induction of the local-global letter task, and four participants whose performance fell below 60.50% on the reinduction of the local-global letter task. Ultimately, we analyzed data from a total of 97 participants (57 females, mean age = 18.9 years).

All participants were native English speakers and consented to participate in the study, which was approved by the Northwestern University Institutional Review Board.

**Materials and procedure overview.** In Experiments 1 and 2, all participants received instructions for the Compound Remote Associates (CRA) task, performed a set of three practice CRA problems, and then attempted the first set of fifty CRA problems (Figure 2). After the first CRA set (set A), participants were randomly assigned to complete one of the three versions of the adapted Navon local-global letter task (i.e., Local, Global, or Match). Participants received instructions and ten practice trials with feedback for their assigned letter task (Figure 3). After completing 160 trials of their assigned letter task, participants attempted the second set of fifty CRA problems (set B).

In Experiment 2, we replicated the procedure of Experiment 1 with some modifications. Specifically, we increased the number of participants, and we counterbalanced the presentation of the two sets (set A and set B) of CRA problems to account for potential set effects. The original order in which participants received the CRA problems in Experiment 1 (set A first, set B second) will be referred to as “order 1” and the counterbalanced CRA problem order (set B first, set A second) will be referred to as “order 2”. Additionally, we reintroduced the letter task after 25 CRA problems in the second set of CRA problems in Experiment 2 to minimize potential attenuation of the attention induction.

Each experiment was approximately one hour long, and they were programmed in PsychoPy (Peirce, 2007).

**CRA problems.** For each CRA trial (Figure 2), participants fixated on a central cross for 1 second, then saw three words (e.g., PINE—CRAB—SAUCE), each presented in lowercase Arial font, 52pt (approximately 1cm in height), on three lines centered on the screen on an achromatic gray background. To solve the CRA problem, participants had to produce a word that can form a compound or common two-word phrase with each of the problem words. Participants pressed the spacebar if they arrived at a solution during the 12-second solution window, and then they verbally provided their solution to the experimenter who scored their response (without providing feedback). If no solution was provided during the solution window, the experiment proceeded to the next problem. After verbalizing their solution, participants indicated how they solved the problem: with insight or with analysis. Insight was described as the spontaneous generation of a solution, which is often accompanied by feeling of surprise and confidence that the solution is correct; typically, one cannot articulate the steps that led to insight. Analysis was described as a deliberate and conscious process; one can report the steps taken to reach solution.

Our descriptions of insight and analytic solutions are similar to those used in other studies that found observable differences in self-reported ratings of solution type (e.g., Bowden & Jung-Beeman, 2003a; Jung-Beeman et al., 2004; Kounios et al., 2006; Kounios et al., 2008; Subramaniam et al., 2009; Wegbreit et al., 2012). Thus, it can be assumed that participants' self-reports of insight and analysis reflected the use of distinct problem solving processes, rather than a preference for one of the terms. Additionally, although fast or immediate responses may feel sudden and surprising, they may not accurately reflect the phenomenological processes involved in insight solving (Cranford & Moss, 2012), and they do not show the same pattern of neural activity (Cranford & Moss, 2011). Thus, we categorized problems solved within two seconds as "fast recognition" instead of insight, and we excluded "fast recognition" solutions from further analyses.

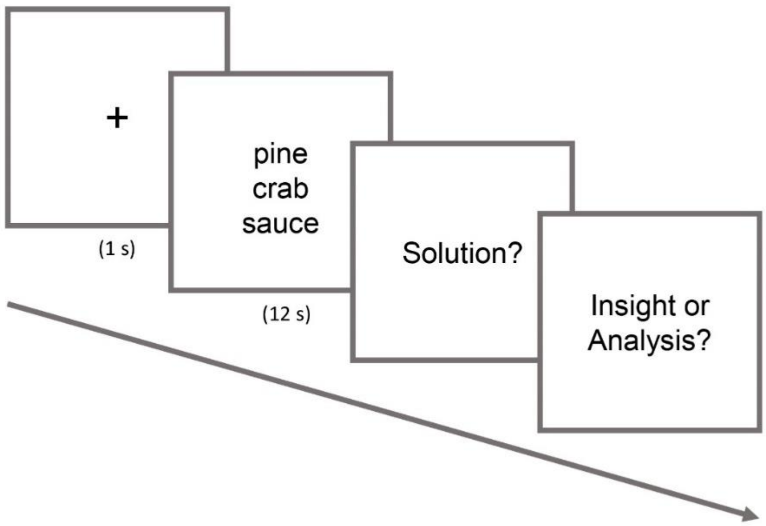


*Figure 2.* Schemata of the Compound Remote Associates (CRA) task. An example of a trial of the CRA task is depicted. Participants were only prompted “Insight or Analysis” if they solved the CRA problem.

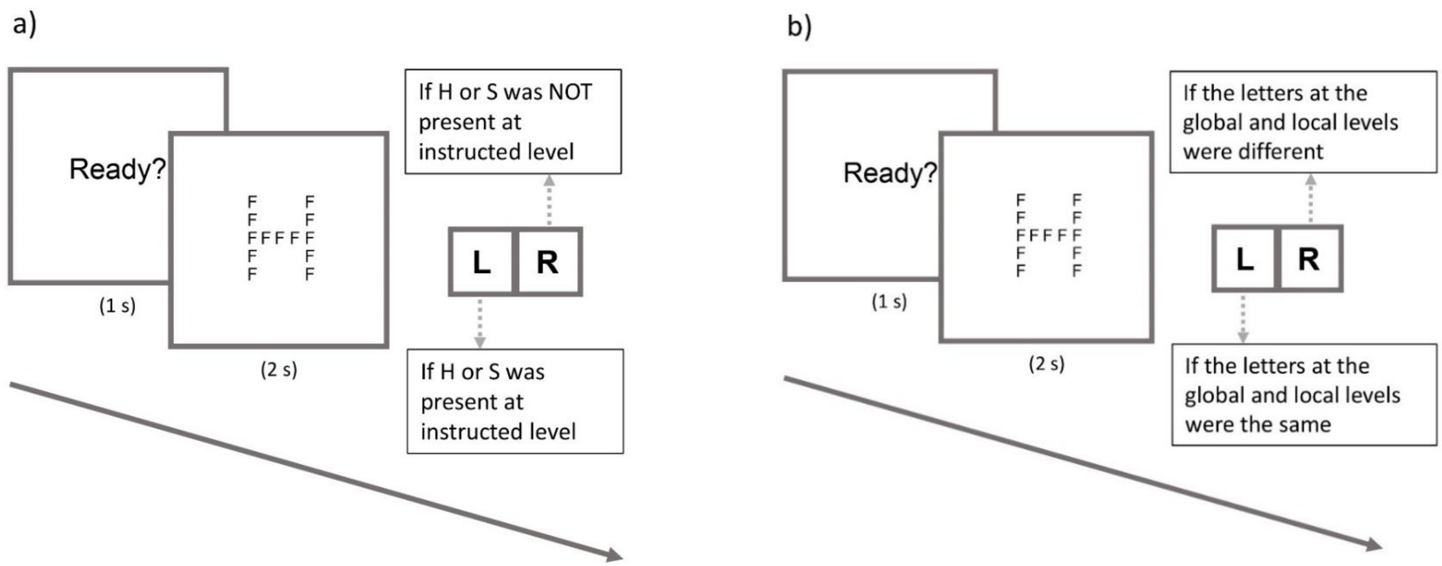


*Figure 3.* Schemata of the local-global letter task. a) An example of a trial of the Local and Global versions of the letter task is depicted. Participants were asked to press the left button (within the 2 second response window) if the hierarchical letter contained an H or S at the level they were instructed to attend (i.e., local or global). Participants were asked to press the right button if the hierarchical letter did not contain an H or S at the level they were instructed to attend. b) This figure exemplifies a trial of the Match version of the letter task. Participants were asked to press the left button if the letters at the local and global levels matched and the right button if the letters at both levels did not match.

**Local-global letter task.** Participants were randomly assigned into one of three conditions (Local, Global, or Match) corresponding to the version of the letter task they would perform. For each version of the letter task, participants were asked to make a "yes" or "no" decision as quickly and accurately as possible according to the following directions:

> In the Local condition, participants responded to whether they detected the target letters (H or S) at the local level of the hierarchical letter stimulus. They responded "yes" (a left button press) if the small letter (Local level) was either an H or an S, or "no" (a right button press) if the small letter was neither an H nor an S.
>
> In the Global condition, participants responded to whether they detected the target letters (H or S) at the global level of the hierarchical letter stimulus. They responded "yes" (a left button press) if the big letter (Global level) was either an H or an S, or "no" (a right button press) if the big letter was neither an H nor an S.
>
> In the Match condition, participants responded to whether the two target levels (Local and Global levels) within a hierarchical letter stimulus matched. They responded "yes" (a left button press) if the big letter (Global target level) and small letter (Local target level) were the same, or "no" (a right button press) if the big and small letters were not the same.

In all three conditions, the same set of hierarchical stimuli was used, such that 50% of the trials should generate a "yes" response for each attention condition. There were eight stimuli in total, each consisting of small letters that form a big letter (see Appendix for examples). The stimuli either contained the same target letter (H or S) at both levels (e.g., H made of H's), contained the target letter at either the Global or Local level with a different non-target letter (either F or C) at the other level (e.g., H made of F's), or contained the same non-target letter at both levels (e.g., F made of F's). The stimulus at the global level was 42mm (H) by 33mm (W) and 6mm (H) by 5mm (W) at the local level. The viewing distance ranged from approximately 55cm to 75cm. The Global letters subtended a visual angle ranging from 4.38° vertically x 3.44 horizontally to 3.21° vertically x 2.52° horizontally. The Local letters subtended a visual angle ranging from 0.62° vertically x 0.52° horizontally to 0.46° vertically x 0.38° horizontally. All letter stimuli were presented in the center of the display against an achromatic gray background.

We calculated congruency effects for the Global and Local conditions (no congruency effect can be calculated for the Match attention condition). In a congruent trial in either Global or Local tasks, the target letter (H or S) at the target level matched the letter at the non-target level. In an incongruent trial, the target letter (H or S) at the target level did not match the letter (F or C) at the non-target level. Congruency effect was calculated for each participant by subtracting the average latency of congruent trials from the average latency of incongruent trials.

Each stimulus was preceded by a "Ready?" prompt fixated at the center of the screen, which remained on the screen for 1 second (see Figure 3). Then, the hierarchical letter stimulus appeared at the center of the screen for 2 seconds, during which participants made their response.

### 2.1.2 Study 1a Results

**Data Analysis.** Performance on the local-global letter task was high and near ceiling (*M* = 96.33%, *SD* = 2.14%) in Experiment 1. Given the general good performance on this task, we chose to remove outliers if their performance fell below three standard deviations from the mean;

however, there were no participants whose performance fell below 89.91%. As in Experiment 1, overall performance on the local-global letter task was high and near ceiling (*M* = 94.15%, *SD* = 10.27%) in Experiment 2. Given the general good performance on this task, we chose to remove outliers if their performance fell below three standard deviations from the mean. Thus, data from five participants who performed below 63.34% were excluded from further analyses. We also excluded data from four participants whose performance on the reinduction of the local-global task fell below 60.5% (*M* = 95.9%, *SD* = 11.8%).

A box plot identified two participants as outliers on CRA solving performance in Experiment 1 (Figure 4a). Data from two participants whose CRA solving performance fell under 61.29% in Experiment 1 were excluded from further analyses. A box plot identified three participants as outliers on CRA (Figure 4b). Data from three participants whose CRA solving performance fell under 68.18% in Experiment 2 were excluded from further analyses.

Shapiro-Wilk test determined that congruency effects in Experiments 1 and 2, as well as CRA solving data (i.e., number of total correct solutions, insight solutions, and analytic solutions) are normally distributed. Thus, we used parametric tests in the following analyses.

All analyses, including the tests for outliers and normality described here, were performed in R.

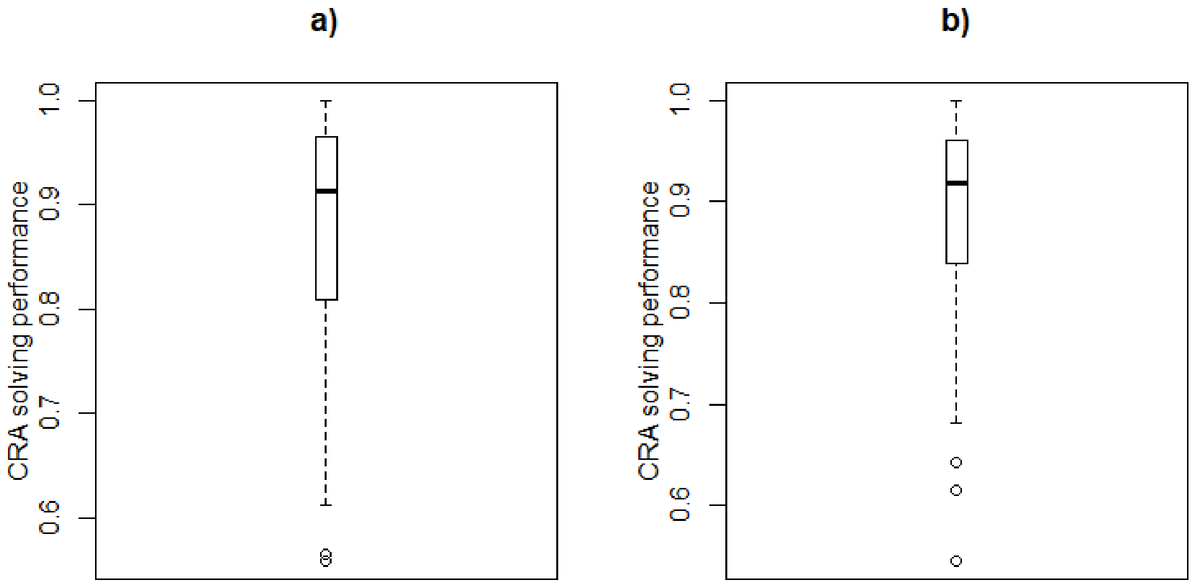


*Figure 4.* Box plots of CRA solving performance in Study 1. a) Box plot of CRA solving performance in Experiment 1. Data from two participants whose performance fell under 61.29% were excluded from the final analysis. b) Box plot of CRA solving performance in Experiment 2. Data from three participants whose performance fell under 68.18% were excluded from the final analysis.

**Local-global letter task performance.** On average, participants in all three conditions in Experiment 1 performed well on the local-global letter task (Table 1). Although participants performed near ceiling in all conditions, a one-way ANOVA showed a reliable difference between conditions on correct responses, $F(2,70) = 5.89$, $p < .01$, $\eta^2 = .14$. A post-hoc Tukey's HSD test revealed that participants who detected Local targets were reliably more accurate than participants who detected Global targets ($p = .03$, $d = .81$) and those who matched target levels ($p < .01$, $d = .87$). There was no reliable difference in accuracy between participants who detected Global targets and those who matched target levels ($p > .5$). Additionally, a one-way ANOVA revealed that there was a reliable difference between the three conditions on latency, $F(2,70) = 32.29$, $p < .01$, $\eta^2 = .48$. Post-hoc comparisons using the Tukey's HSD test revealed that the participants who matched target levels were reliably slower than those who detected the Local targets ($p < .01$, $d = 1.81$) and those who detected the Global targets ($p < .01$, $d = 1.97$).

Participants in Experiment 2 performed similarly well on the letter task (Table 2); specifically, participants improved in speed in their second exposure to the letter task, but they were near ceiling in their accuracy. There were no reliable differences in the number of correct responses between any of the three letter task conditions within the initial induction or during reinduction, both $F(2,95) < 1.0$. A one-way ANOVA revealed a reliable difference between the three conditions on latency, $F(2,94) = 18.89$, $p < .01$, $\eta^2 = .29$. A post-hoc Tukey's HSD test revealed that, in the initial induction, participants who matched target levels performed reliably slower than those who detected Local targets ($p < .01$, $d = 1.16$) and those who detected Global targets ($p < .01$, $d = 1.42$). The same pattern of results was found for the second induction of the letter task, $F(2,94) = 15.07$, $p < .01$, $\eta^2 = .24$; participants who matched target levels performed reliably slower than those who detected Local targets ($p < .01$, $d = 1.01$), and those who detected Global targets ($p < .01$, $d = 1.33$). A repeated-measures ANOVA revealed that participants were not more accurate in the reinduction compared to the initial induction, $F(2,94) < 1.0$, suggesting that participants performed near ceiling. Another repeated-measures ANOVA determined that participants were reliably faster in the reinduction, $F(1,94) = 135.22$, $p < .01$, $\eta_p^2 = .59$, but the interaction between time of induction and condition on latency was not reliable, $F(2,94) = 1.43$, $p = .24$.

**Congruency effects.** In Experiment 1, participants who performed either Local or Global tasks generally responded more quickly on trials where the letters were congruent at both levels than when they were incongruent, $F(1,48) = 25.03$, $p < .01$, $\eta_p^2 = .34$. Additionally, there was a reliable interaction between condition (i.e., Global vs Local) and trial type (i.e., congruent vs incongruent), $F(1,48) = 6.77$, $p = .01$, $\eta_p^2 = .12$, such that participants who detected Global targets had larger congruency effects (i.e., a bigger difference in latencies between incongruent trials and congruent trials; $M = 34$ ms, $SD = 27$ ms) than participants who detected Local targets ($M = 11$ ms, $SD = 35$ ms).

To evaluate congruency effects in Experiment 2, we averaged the latencies for incongruent trials and congruent trials across both inductions of the letter task. Participants who performed either Local or Global tasks in Experiment 2 responded faster when the trials were congruent than when they were incongruent, $F(1,63) = 41.82$, $p < .01$, $\eta_p^2 = .40$. Again, we found a reliable interaction between condition (i.e., Global vs Local condition) and trial type (i.e., congruent vs incongruent trials), $F(1,63) = 5.70$, $p = .02$, $\eta_p^2 = .08$. Thus, consistent with

Experiment 1, participants who detected Global targets had larger congruency effects (*M* = 34 ms, *SD* = 25 ms) than participants who detected Local targets (*M* = 16 ms, *SD* = 36 ms).

Table 1

*Local-Global (Letter) Task Performance in Experiment 1*

| Letter Task Condition | % Correct | Mean latency |
|---|---|---|
| Local<br>(*n* = 26) | 97.2%<br>(1.8%) | 576 ms<br>(69 ms) |
| Global<br>(*n* = 23) | 95.8%<br>(1.8%) | 563 ms<br>(69 ms) |
| Match<br>(*n* = 24) | 95.4%<br>(2.4%) | 730 ms<br>(99 ms) |

Note: Mean (and SD) percent of trials with correct responses and corresponding latencies for each letter task condition (local, global, and match) for Experiment 1.

Table 2

*Local-Global (Letter) Task Performance in Experiment 2*

| | First Induction | | Second Induction | |
|---|---|---|---|---|
| Letter Task Condition | % Correct | Mean latency | % Correct | Mean latency |
| Local<br>(*n* = 32) | 96.8%<br>(1.9%) | 608 ms<br>(78 ms) | 96.6%<br>(2.7%) | 563 ms<br>(83 ms) |
| Global<br>(*n* = 33) | 96.5%<br>(3.1%) | 587 ms<br>(78 ms) | 96.4%<br>(3.3%) | 548 ms<br>(66 ms) |
| Match<br>(*n* = 32) | 96.1%<br>(3.1%) | 701 ms<br>(82 ms) | 95.8%<br>(3.1%) | 646 ms<br>(81 ms) |

Note: Mean (and SD) percent of trials with correct responses and corresponding latencies for each letter task condition (local, global, and match) for Experiment 2.

**CRA problem-solving performance.** Participants in Experiment 1 solved 32.6% of CRA problems correctly in the first set (set A) and solved 37.8% correctly in the second set (set B; after the global-local task) overall. In total, participants averaged 35.4% correct solutions and 5.6% incorrect solutions. Of all correct solutions, 57.2% were solved with insight, 40.0% were solved with analysis, and 2.8% were fast recognitions (problems solved in less than 2 seconds) that we excluded from further analyses.

In Experiment 2, participants correctly solved 35.8% of the problems in the first set of CRAs (collapsed across both orders) and 38.9% in the second set of CRAs (after the letter task). In total, participant averaged 37.3% correct solutions and 4.9% incorrect solutions. Of all correct solutions, 47.2% were solved with insight, 48.6% were solved with analysis, and 4.2% were fast recognitions, which were excluded from further analyses. [When all participants are included, participants correctly solved 35.2% of the problems in the first set of CRAs and 37.9% of the problems in the second set of CRAs. Of their correct solutions, 46.9% were solved with insight, 48.9% were solved with analysis, and 4.2% were fast recognitions.]

Our goal in Experiments 1 and 2 was to determine whether attending to the Local, Global, or both levels of hierarchical stimuli can affect whether people solve problems with analysis or insight. In Experiment 1, we analyzed the number of correct solutions with a 2 (time; before vs after attention task) x 2 (solution type) x 3 (condition) mixed factorial ANOVA. Overall, there was a reliable main effect of time such that, on average, participants tended to solve more problems in set B than in set A, $F(1,70) = 25.26$, $p < .01$, $\eta_p^2 = .27$. There was a reliable main effect of solution type such that participants tended to solve more problems with insight than analysis overall, $F(1,70) = 17.25$, $p < .01$, $\eta_p^2 = .20$, similar to most studies using these stimuli (for review, Kounios & Beeman 2014). The 3-way interaction between time, type of solution, and intervening attention task was not reliable, $F(2,70) = 1.31$, $p = .28$, $\eta_p^2 = .04$. None of the 2-way interactions in the omnibus ANOVA were reliable ($p$'s >.25).

In Experiment 2, we analyzed the number of correct solutions with a 2 (time; before vs after attention task) x 2 (solution type) x 2 (order) x 3 (condition) mixed factorial ANOVA to capture potential variance due to a set effect. Overall, there was a reliable interaction between time and order, $F(1,91) = 61.00$, $p < .01$, $\eta_p^2 = .40$; participants across all conditions tended to solve more CRA problems in set B (as in Experiment 1, order 1) and solved fewer CRA problems in set A. Despite the set effect, there was a reliable main effect of time across the 2 orders, $F(1,91) = 3.98$, $p = .05$, $\eta_p^2 = .05$, such that participants in all conditions tended to solve more problems after the letter task. Because there was a set effect, we kept order as a variable in all analyses, but we will not further discuss it (because all such effects are attributable to the specific problems within the sets). The 4-way interaction between time, solution type, order, and condition was not quite reliable, $F(2,91) = 1.89$, $p = .16$, $\eta_p^2 = .04$. There were no reliable 3-way interactions (all $p$'s >.30), nor were there any reliable 2-way interactions (all $p$'s >.25). Finally, there was no main effect of solution type, $F < 1.0$, unlike Experiment 1 (and most prior studies using CRA problems).

In Experiment 1, we examined the predicted changes in solving in individual 2 (time) x 2 (solution type) ANOVAs and planned paired two-tailed t-tests for each attention condition. In Experiment 2, we examined changes in problem solving in individual 2 (pre vs post letter task) x 2 (solution type) x 2 (order) ANOVAs and 2 (time x order) ANOVAs for each solving type (insight or analysis) in each attention condition. The individual ANOVAs for each letter task group revealed improvements on either analytic or insight solving, depending on which letter task was performed, as well as an overall improvement in the total number of CRA problems solved following all letter tasks (Table 3).

We hypothesized that participants who detected Local targets would increase analytic solving following the Local task regardless of the interpretation (i.e., selective attention or narrowed scope of attention). In Experiment 1, a pairwise comparison revealed that there was a marginally reliable increase in analytic solving after the local version of the letter task, $t(25) = 18.3$, $p = .06$, $d = .36$. The increase in insight solving was similar but not reliable, $t(25) = 1.25$, $p = .22$, nor was the interaction between type of solving and time reliable ($F < 1.0$). There was a reliable main effect of time, $F(1,25) = 9.42$, $p < .01$, $\eta_p^2 = .26$. That is, participants who detected Local targets were more likely to solve more problems in set B than in set A. There was also a marginally reliable main effect of solution type, $F(1,25) = 3.86$, p = .06, $\eta_p^2 = .19$; participants who detected Local targets tended to solve more problems with insight than with analysis overall, though not quite reliably.

Based on this trend, we expected participants to solve more problems analytically after performing the Local task in Experiment 2. However, a 2 (time) x 2 (order) ANOVA for analytic solving showed no difference on analytic problem solving, $F(1,30) = 1.69$, p = .20, $\eta_p^2 = .05$. Participants in Experiment 2 solved roughly the same number of problems with insight before and after responding to Local targets, $F(1,30) < 1.0$. Participants who detected Local targets tended to solve more problems in the second set of CRAs than in the first, though this was only marginally reliable, $F(1,30) = 3.95$, $p = .06$, $\eta_p^2 = .12$.

Table 3

*Change in Insight and Analytic Solutions of Compound Remote Associates (CRA) Problems in Study 1*

| | | Before Letter Task | | After Letter Task | | Change (After – Before Letter Task) | |
|---|---|---|---|---|---|---|---|
| | Condition | Insight | Analysis | Insight | Analysis | Insight | Analysis |
| Expt 1 | Local (*n* = 26) | 9.81 (4.27) | 6.77 (4.25) | 10.92 (4.57) | 8.19 (3.85) | 1.11 | 1.42 |
| | Global (*n* = 24) | 9.17 (3.94) | 6.79 (3.71) | 9.58 (5.27) | 8.50 (5.15) | 0.41 | 1.71* |
| | Match (*n* = 23) | 9.30 (2.98) | 5.52 (3.64) | 11.48 (3.90) | 6.26 (3.48) | 2.18* | 0.74 |
| Expt 2 | Local (*n* = 32) | 8.09 (3.68) | 9.06 (4.75) | 8.22 (4.96) | 10.16 (5.47) | 0.13 | 1.10 |
| | Global (*n* = 33) | 9.21 (4.81) | 8.06 (3.82) | 7.88 (4.08) | 10.03 (5.19) | -1.33 | 1.97* |
| | Match (*n* = 32) | 9.78 (4.56) | 8.13 (4.33) | 9.69 (4.83) | 9.03 (5.76) | -0.09 | 0.90 |

*$p < .05$

Notes: Mean (and SD) percent of correct solutions reported as insight or analysis in each letter task condition in Experiments 1 and 2. All three groups improved overall (fast recognition responses are excluded).

A hypothesis consistent with some literature suggests that attending to Global stimuli should result in defocused attention conducive to insight. Thus, participants should increase insight solving after detecting Global targets. In Experiment 1, a pairwise comparison did not show a reliable increase in insight solving, $t(23) = -.54$, $p > .50$ and does not provide support for this hypothesis. This effect was replicated in Experiment 2: participants solved ***fewer*** problems with insight after the Global task than at baseline, although this effect was not quite reliable, $F(1,31) = 2.86$, $p = .10$, $\eta_p^2 = .08$.

Alternatively, attending to targets at the Global level may still require selective attention, just to a spatially broad component of the display. If our Global task induces selective attention, participants should increase analytic solving after responding to Global targets. Indeed, in Experiment 1, a pairwise comparison revealed a reliable increase in analytic solving following the Global task, $t(23) = -3.17$, $p < .01$, $d$=.47, providing support for this hypothesis. There was a reliable main effect of time, $F(1,23) = 12.43$, $p < 0.01$, $\eta_p^2 = .18$, such that participants who detected Global targets tended to solve more problems in set B than in set A in Experiment 1. This effect was not replicated in Experiment 2, $F(1,31) < 1.0$ due to a reliable crossover interaction between time and solution type, $F(1,31) = 6.53$, $p = .02$, $\eta_p^2 = .17$. The main effect of solution type was not reliable in neither Experiment 1, $F(1,23) = 1.31$, $p = .27$, nor Experiment 2, $F(1,31) < 1.0$, suggesting that participants who detected Global targets were not more likely to solve CRA problems with either insight or analysis overall. As in Experiment 1, after detecting Global targets in the letter task, participants in Experiment 2 solved ***more*** problems analytically than they did at baseline, indicated in a reliable 2 (time) x 2 (order) ANOVA on the number of analytic solutions, $F(1,31) = 7.07$, $p = .01$, $\eta_p^2 = .19$.

One hypothesis is that matching Global and Local levels spreads attention across both levels. If so, the spreading of attention caused by the Match task should be conducive to insight solving. A pairwise comparison lent support for this hypothesis in Experiment 1, revealing a reliable increase in insight solving following the Match attention task, $t(22) = -2.86$, $p < .01$, $d = .62$, compared to baseline. However, this effect was not replicated in Experiment 2, and a 2 (time) x 2 (order) revealed no difference in the number of solutions with insight following the Match task, $F(1,30) = .02$, $p > .5$ compared to baseline.

Another hypothesis is that, in order to match across both levels, participants must briefly attend to one level while inhibiting input from the other level before quickly switching their attention to the other level, again inhibiting interference from the other level. If so, the selective attention caused by the Match task should be conducive to analytic solving. However, a pairwise comparison revealed no reliable increase in analytic solving following the Match task in Experiment 1, $t(22) = -.44$, $p = .66$, nor in Experiment 2, $F(1,30) = 1.73$, $p = .20$. There was a reliable main effect of time in Experiment 1, $F(1,22) = 6.82$, $p = .02$, $\eta_p^2 = .35$, such that participants who performed the Match task were more likely to solve more problems in set B than in set A. However, this effect was not reliable in Experiment 2, $F(1,30) = 1.12$, $p = .30$. There was a reliable main effect of solution type in Experiment 1, $F(1,22) = 22.20$, $p <.01$, $\eta_p^2 = .45$, such that participants who matched target levels were more likely to solve with insight than with analysis overall, but this effect was not reliable in Experiment 2, $F(1,30) < 1.0$.

### 2.1.3 Study 1a Discussion

Participants in both experiments solved more CRA problems after performing any version of the local-global letter task, and they increased in either insight or analytic solving depending on which version of the task they performed.

In Experiment 1, participants in all three groups solved more problems following the letter task than they did at baseline. The letter tasks all could have had some unintended facilitation effect, enhancing attention or motivating participants in ways that improved problem solving. However, it may also mean that, despite efforts to equate the two problem sets, the second set was easier, resulting in a problem set effect. Experiment 2 confirmed the presence of a problem set effect in Experiment 1 (set B slightly easier than set A), but participants still tended to solve more problems after the letter tasks than before, suggesting that the local-global letter tasks generally facilitated solving on subsequent CRA problems. This finding could indicate that all three attention tasks facilitated problem solving in the second set of problems.

As is typical with the CRA problems, all three groups solved more problems overall with insight than with analysis (e.g., Kounios & Beeman, 2014) in Experiment 1. We did not find this effect in Experiment 2. However, the critical issue is how people changed in problem solving processes following the attention tasks.

We expected that selective attention to the Local level of hierarchical stimuli would either narrow the focus of attention or increase the selectivity of attention, either of which would increase analytical problem solving. However, in both Experiments 1 and 2, the increase in the number of problems solved analytically was not quite reliable. In fact, these participants demonstrated a similarly (also not quite reliable) increase in problems solved with insight. However, it is possible that an overall set effect (if problem set B was easier than set A) was masking a specific but small facilitatory effect of the Local task on subsequent analytic solving.

There were competing hypotheses regarding the effect of attending to the Global level of hierarchical stimuli on subsequent problem solving. Some literature suggests that attention to the Global letter should broaden attention, diluting the selectivity within the broad focus, thus promoting more insight problem solving. We found the opposite effect in both experiments, even when considering the set effect in Experiment 2: Participants who detected Global target letters solved more problems with analysis, not with insight. In Experiment 2, there was also a reliable interaction between time (baseline vs after letter task) and solution type (analysis vs insight), such that detecting Global targets affected solving differently: reliably increasing analytic solving while (non-reliably) decreasing insight solving. This finding supports the second hypothesis that responding to the Global level still requires selective attention even though the target stimulus is more spatially broad than the Local level.

Recall that the congruency effect provides an index of the selectivity of attention. In fact, participants identifying Global letters showed a greater congruency effect in both experiments – more slowing when the non-target level mismatched the target level of the display – than did participants identifying Local targets. This makes sense given that participants cannot take in the Global targets without also seeing the local elements, whereas it is possible to perceive the Local targets without seeing the global letter they form. Thus, the Global task may have demanded more attentional selectivity than the Local one, consistent with the increase in analytic solving following the Global task.

There were also two contrasting hypotheses concerning the Match task. If matching across both Global and Local levels requires less attentional selection (i.e., participants can spread attention and take in both levels simultaneously), participants should increase insight solving. In contrast, if matching requires rapidly switching between the two levels, we expected an increase in analytical solving. Evidence was more consistent with the former hypothesis: Participants who performed the Match version of the letter task increased solving with insight but not with analysis.

Before we interpret these results in the General Discussion, we wanted to again verify whether congruency effect is larger when detecting targets at the Global level compared to the Local level; this is important because it implies that people who perform the Global task must engage in more selective attention than if they perform the Local task. Additionally, we wanted to ensure that the congruency effects that were obtained were not influenced by the baseline verbal problem solving task, which preceded the letter tasks in Experiments 1 and 2. Thus, Study 1b repeated the local-global letter task with new participants, without any Compound Remote Associates problems.

## 2.2 Study 1b: Replication of Congruency Effects

### 2.2.1 Study 1b Methods

**Participants.** Sixty-nine undergraduate students (39 females, average age = 18.44) participated in this experiment for partial course credit. We excluded four participants from further analyses due to noncompliance (e.g., interrupted experimentation to answer their phones or could not pass the practice set in two tries with at least 60% accuracy) during the experiment. We also excluded one participant whose average latency on the local-global task was three standard deviations greater than the mean (*M* = 780 ms, *SD* = 74 ms). The final sample consisted of 64 participants (36 females, average age = 18.44). All participants consented to participate in the study, which was approved by the Northwestern University Institutional Review Board.

**Materials and Procedure.** Study 1b used the same local-global letter task from Experiments 1 and 2 (see Figure 3, and 2.1.1. for a complete description of the local-global letter task). Participants were randomly assigned to receive either the Local or Global version of the local-global letter task. The experiment was approximately 30 minutes long, and it was programmed in PsychoPy (Peirce, 2007).

### 2.2.2 Study 1b Results and Discussion

Participants who performed either the Local or Global attention tasks responded more quickly when the trials contained congruent targets than when the trials had incongruent targets, $F(1,62) = 59.48$, $p < .01$, $\eta_p^2 = .49$. There was also a reliable interaction between condition (i.e., Global vs Local) and trial type (i.e., congruent vs incongruent), $F(1,62) = 5.04$, $p = .03$, $\eta_p^2 = .08$. Thus, consistent with both Experiments 1 and 2, participants who detected Global targets had a larger congruency effect (*M* = 39 ms, *SD* = 23 ms) than participants who detected Local targets (*M* = 21 ms, *SD* = 39 ms).

Thus, we confirmed, through congruency effects, that our version of the Global task pushes people toward more selective attention (Figure 5). To further examine the relationship between selectivity in the letter task and problem solving tendency, we conducted additional analyses relating individual differences across the two tasks. These are described below as Study 1c, although the data are from Experiments 1 and 2.

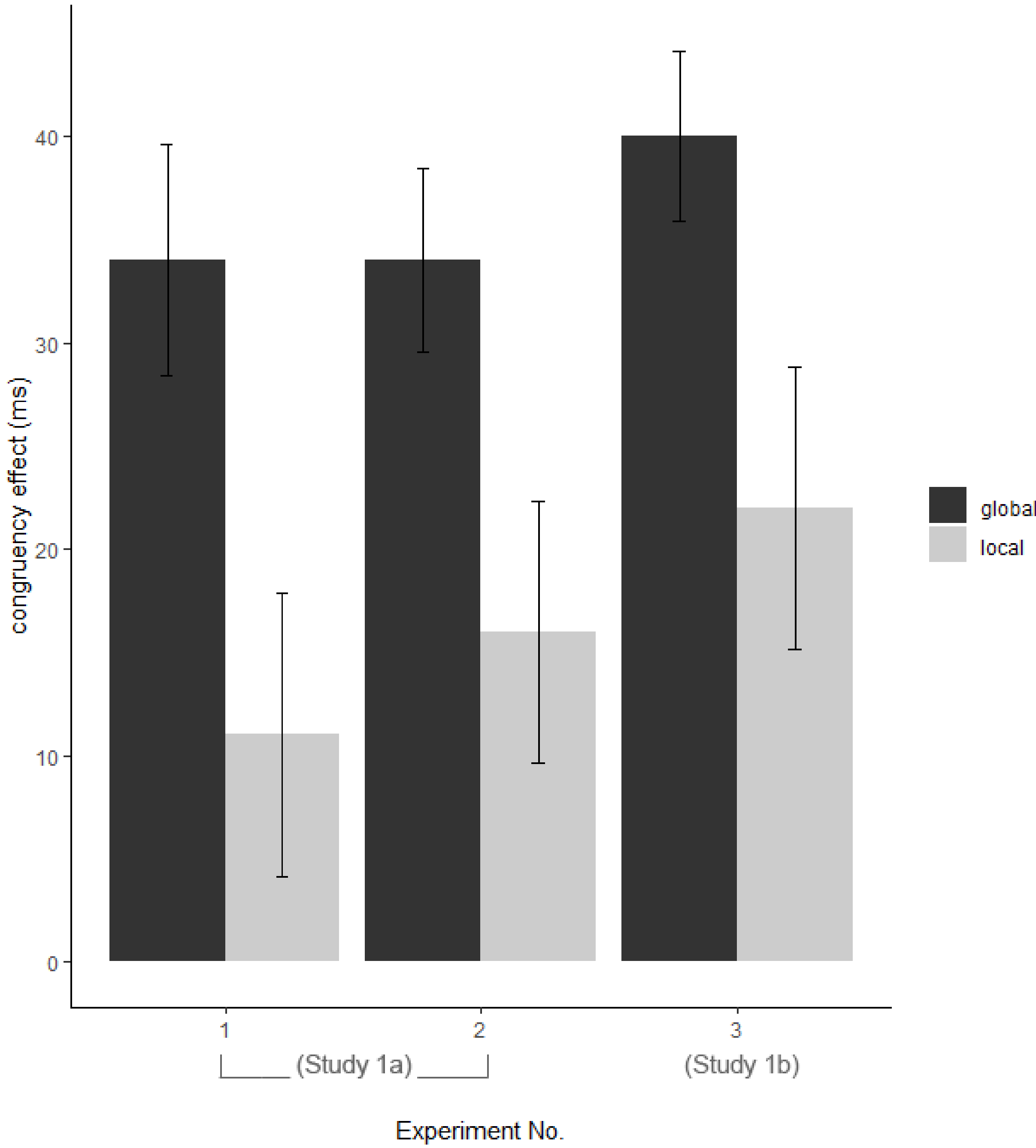


*Figure 5.* Mean congruency effects (incongruent minus congruent latency, in ms) when detecting local versus global target letters in Study 1b.

## 2.3 Study 1c: Individual Differences in Congruency Effects and Problem Solving

### 2.3.1 Study 1c Methods

**Participants.** We combined across data from participants who performed either the Global or Local task (but not the Match task, as it does not provide a measure of congruency) from Experiments 1 and 2. In total, we analyzed data from 115 participants from Study 1a (68 females, mean age = 18.63).

**Data Analysis.** Congruency effects were correlated post-hoc with the baseline number of problems solved correctly with analysis or with insight, before they performed the Local or Global letter task (in the Match task, "congruency" provides the basis for the Yes versus No response). In these one-tailed correlations, we z-scored the number of problems solved with analysis or insight at baseline within each order (i.e., original or counterbalanced) across both Local and Global task conditions to account for any differences in solving due to set effects (i.e., in Experiment 1 all participants received set A at baseline, whereas half the participants received set A and the other half received set B at baseline in Experiment 2). To ensure the congruency effects were on an equivalent scale, we also z-scored congruency effects across Local and Global conditions when combining congruency effects from both experiments.

### 2.3.2 Study 1c Results

Differences in selective attention as indexed by congruency effects were related to a bias toward one problem solving process over another. Specifically, insight problem solving at baseline was positively correlated with congruency effects (i.e., less selective attention) for people who detected Global targets, $r(55) = .22$, $p = .05$ (Figure 6a). Conversely, analytic problem solving at baseline was negatively correlated with congruency effects (i.e., more selective attention) for people who detected Local targets, though this finding was not quite reliable, $r(56) = -.19$, $p = .08$ (Figure 6b). Analytic solving at baseline was slightly but reliably negatively correlated with congruency effects (i.e., more selective attention) for participants across Global and Local conditions combined, $r(113) = -.16$, $p = .05$ (see Figure 6c). Thus, solving type at baseline was related to the demonstrated selectivity of attention on the following Local or Global letter task.

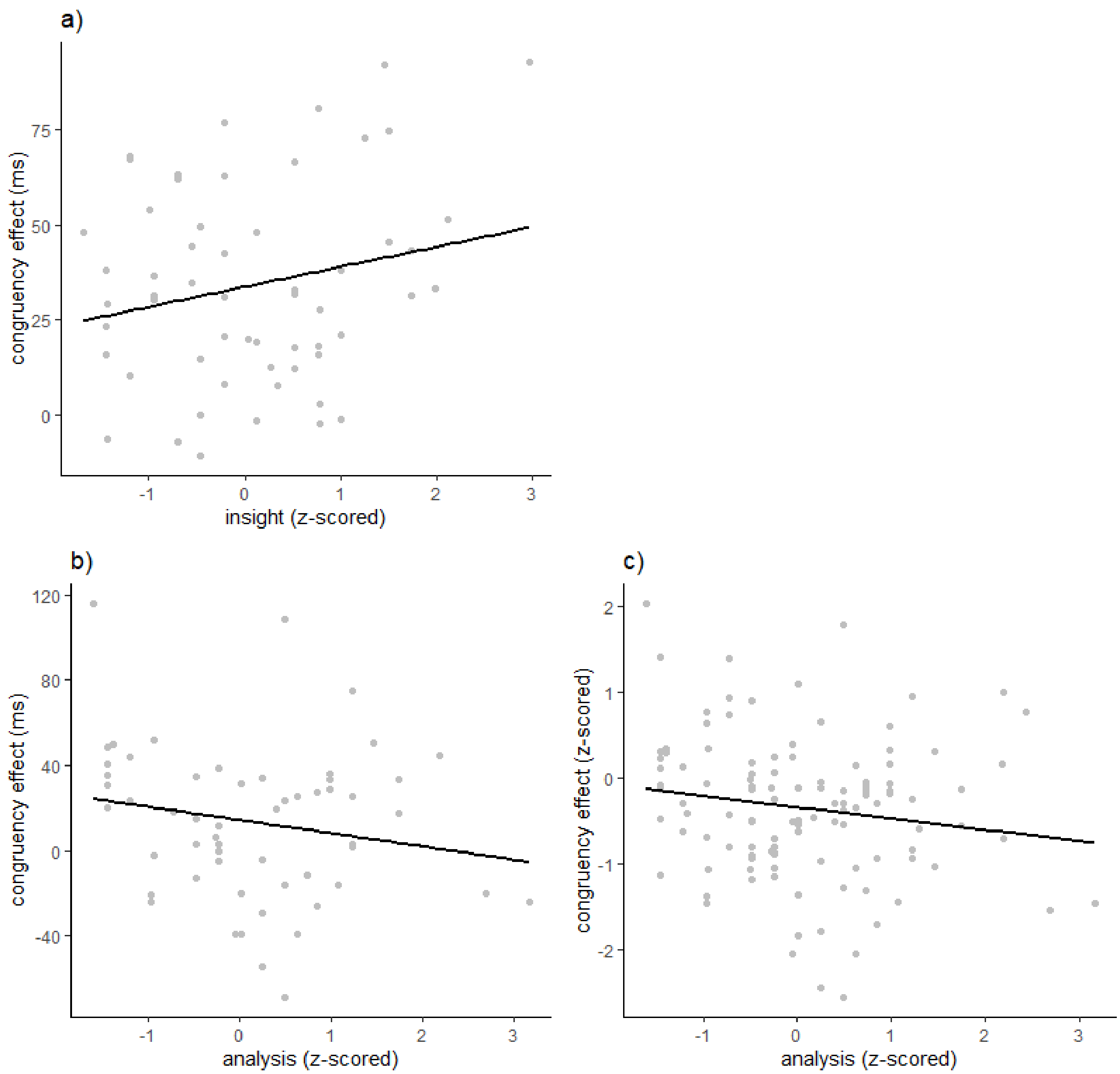


*Figure 6.* Correlations between congruency effects and insight and analytic solving in Study 1c. a) Larger congruency effects, indicating less selective attention, are positively correlated with number of verbal problems solved with insight. b) There was a trend towards a negative correlation between participants' congruency effect size and number of verbal problems solved with analysis. c) Smaller congruency effects, indicating more selective attention, were negatively correlated with number of verbal problems solved with analysis**.**

**2.4 Study 1: General Discussion**

In Study 1, we tested how attention to either local, global, or both levels of visual stimuli relate to verbal problem solving performance. The findings from Experiments 1 and 2 suggest that, consistent with prior results using different tasks (Wegbreit et al., 2012), people shift the way they solve problems, either with analysis or insight, after they perform a visuospatial attention task. Specifically, performing a visuospatial task that encourages more selective attention subsequently increases analytic problem solving. In addition to direct manipulation, correlational findings also support the idea that, in general, differences in attention are related to problem solving (e.g., Ansburg & Hill, 2003; Rowe et al., 2007). In the current study, more selective attention, as indexed by smaller congruency effects, was related to more analytic solutions on verbal problems. In contrast, less selective attention, demonstrated by larger congruency effects, was related to more insight solutions on verbal problems. These differences need not be intentional; the problems used here can be solved either way, and the processes involved probably function in parallel, but the process that ultimately leads to solution can vary.

We started with two competing hypotheses regarding how attending to the Global level of hierarchical stimuli may affect how people subsequently solve problems: if attention is spatially and conceptually broadened by inducing a global precedence, people should solve more problems with insight after responding to Global targets. But, if attention to the Global level instead requires people to inhibit Local targets to select the Global, the increase in selective attention should encourage people to solve more problems analytically after responding to Global targets. The results of two experiments support the latter hypothesis.

Since global processing and insight both depend on right hemisphere activity to some degree, participants who focus on the global level would engage the right hemisphere, which should in theory facilitate insight solving. However, as we previously posited, visual processing and problem solving occur within disparate domains and have different neural substrates. Thus, even if a hemispheric relationship were involved, it would have to be a very general effect. Additionally, it does not appear that modulating problem solving is as simple as "turning on" the right hemisphere. For example, when using mood to manipulate problem solving, positive mood did not "turn on" the right hemisphere, but rather altered cognitive-control related regions (i.e., ACC) in a way that facilitated attention to weaker ideas or associations, which are often activated by semantic processing in the right hemisphere (Subramaniam, 2008; Subramaniam et al., 2009). It is, therefore, more likely that cognitive control and attention are the mechanisms that underlie the ability to integrate distant associations, and attention may be how this ability is most directly related to local and global processing.

Due to the similarities (as discussed in the Introduction) in attention-related processes between global processing and insight problem solving, one might expect that detecting Global letters would boost insight solving on verbal problems. Instead, we observed that responding to Global targets in our local-global letter task enhanced analytic solving. This result is consistent with an alternative interpretation: Attention to the Global level of hierarchical letter stimuli while simultaneously ignoring the Local level encourages increased selective attention conducive to analytic problem solving.

Moreover, this interpretation is consistent with prior evidence. For example, when people attended to incongruent (compared to congruent) trials at the Global level, they had heightened activity in the MePFC monitoring network and lateral PFC (Hechtman, 2015), which has a role in monitoring and suppressing interference (Blasi et al., 2006). Reliable activity in these areas was not found when people attended to incongruent versus congruent trials at the local level (Hechtman, 2015). Even though attention to the Global level may be spatially broad, people need to increase attentional selection, or at least require greater contributions from areas involved in selection, when attending to Global targets than when attending to Local targets. Additionally, recruitment of the MePFC monitoring network might also suggest people need to exert top-down cognitive control to filter interference from the Local level when attending to the Global level.

Experiments from our lab previously found that posterior areas typically involved in focused attention also showed increased neural activity when people responded to the local level of incongruent compared to congruent hierarchical information (Hechtman, 2015). The same areas were implicated in analytic solving (Kounios et al., 2008). Given these prior findings, it is surprising that detecting Local targets in our study resulted in only a non-reliable increase in analytic solving. However, it is likely attention to the Local level requires less selection than when attending to the Global level. Additionally, it is also possible that attention to the Local level does not register as much conflict as when we attend to the Global level. In other words, we may not need to exert top-down cognitive control to maintain attention on the Local level because the Global level does not present as much interference. This idea is supported by our study: the congruency effects for the Local task were reliably lower than that for the Global task in three experiments, suggesting that it was easier for participants to maintain attention on Local stimuli when there was conflicting information at the other level (during the Local task). In contrast, it was more difficult for participants to maintain attention on Global stimuli when information from the other level interfered; thus, they had overall greater congruency effects.

It may be claimed that the larger congruency effect found in the Global task is the result of spatial spreading of visual attention, and insight solving is the product of spatially spreading conceptual attention (e.g., Rowe et al., 2007). While this interpretation may explain why larger congruency effects correlate with insight solving in our individual differences analyses, it cannot explain why the Global task facilitated analytic solving in both experiments.

It is unlikely that any discrepancies between Experiment 1 and Experiment 2 were due to any differences in letter task performance. In both experiments, participants performed nearly at ceiling on each version of the letter task, showing similar patterns of accuracy in each group. Additionally, in both experiments, participants who matched local and global levels performed reliably slower, on average, than participants in the Local and Global conditions.

In Experiment 2, participants did not increase insight solving after matching target levels; thus, we did not replicate this finding from experiment 1. Since participants in the Match condition in Experiment 2 performed similarly on the letter task to those in Experiment 1, it is unlikely that the failure to replicate was due to any differences on the letter task. It is also unlikely that the inconsistency is due to the problem set effect; participants in the Match condition who received the original order of CRA problems in Experiment 2 did not reliably change their insight solving after the Match task, but they did reliably increase their analytic solving. We found the reverse pattern for participants in the Match condition who performed the counterbalanced order of CRA problems, though neither change in solving was reliable.

We are not claiming that any task that induces "global processing" will also facilitate analytic solving. It is possible that the specific pattern of effects observed in our study occurs only for the specific version of the letter task we used, which required people to increase selective attention when detecting global targets. In fact, other studies that used more traditional versions of the Navon letter task did not report reliable differences in congruency effects when making decisions at either global or local levels (Zabelina et al., 2016).

There are several significant differences between our version of the local-global letter task and the typical Navon letter task. For one, our task was a block design during which participants were cued to only one of the two levels or had to match between local and global levels. For another, in our task, participants detected one of two target letters at one level (so that the responses for all three letter tasks were equivalent "yes" or "no" responses). In other versions of the Navon letter task, participants report typically which of the target letters they saw first or the level at which the target letter appeared. It could be that these distinctions result in the congruency effects reported in our studies, which, due to global precedence effects, may not be as strong or calculable in a typical Navon task.

Our interpretation of our how our local-global letter task modulated selective attention and how this influenced problem solving processes resulted from the subsequent changes in problem solving. To explain how the letter task modulated selective attention, however, would require a more direct examination. For example, people could perform the letter task, which may influence their subsequent performance on visual attention tasks that require more selective attention, such as the central flanker task, versus less selective attention, such as the rapid object identification task. Specifically, if the Global attention task is inducing selective attention, we should expect improved performance on the flanker task but poorer performance on the rapid object identification task. In an unreported follow-up study, we did not find that participants performed better on the central flanker task after performing the Global version of the letter task. Almost all participants, however, performed near ceiling on both attention tasks. Thus, the null effect may be due to an inability to detect small changes in selectivity using the flanker task.

We can also focus on the task with the most consistent effect and vary the parameter that we think is driving the effect; specifically, we could alter the amount of competition present, and hence, vary the amount of selection required. In Study 2, we modulated the Global version of the task such that either the global or local elements of the stimuli were more visually salient to the viewer. By manipulating the visual salience of the features of the Global hierarchical stimulus, we were able to create a condition with little conflict and another with more conflict. Thus, we can observe whether low or high amounts of interference, or the degree of selective attention one must continually employ, can decrease or increase subsequent analytic solving.

## 2.5 Study 2: Selective Attention to Global Hierarchal Stimuli with Local-Salient Features Increases Analytic Problem Solving

### 2.5.1 Study 2 Introduction

In Study 1, we found that, in two experiments, people reliably increased analytic solving after performing a visual attention task in which they judged information at the global level. A putative explanation for this finding is that attention to the global level demanded more selective attention, which induced an attentional state that was more conducive to analytic solving. Congruency effects—the difference in latencies of incongruent and congruent trials—provided additional support for this explanation. Across three experiments, we found that attention to the Global level produced greater congruency effects, which suggests that people needed to make their attention more selective when the hierarchical stimulus contained conflicting information across both levels (i.e., incongruent trials). When we looked at individual differences in attention and problem solving, we found that people with smaller congruency effects (i.e., people who had more selective attention in general, and were thus quicker at judging conflicting letter stimuli) tended to solve more problems with analysis at baseline. Conversely, people with larger congruency effects (i.e., people who had less selective attention in general, and were thus slower at judging conflicting letter stimuli) tended to solve more problems with insight at baseline.

Given that only the Global version of the local-global letter task produced consistently reliable results in Study 1, we chose to focus on exclusively manipulating attention to the global level of information to modulate subsequent analytic problem solving (i.e., Global letter task) in Study 2. Specifically, we can manipulate the degree of selective attention required to attend to the global level by varying the amount of competition present within the hierarchical stimulus itself. Previous studies have shown that the latency advantage in identifying global versus local information can be affected by visual factors such as visual angle (Navon & Norman, 1983; Kinchla & Wolfe, 1979) and global goodness (Lasaga & Hecht, 1991). Thus, one way to manipulate the competition within the stimulus is to vary the size of the global letter stimulus and its components (i.e., the local or small letters).

As in Study 1, we used Compound Remote Associates (CRA) problems to measure changes in insight and analytic solving (i.e., at baseline and after performing the Global letter task). We manipulated the selectivity of attention using local-salient (i.e., the local letters are large, which should engender more conflict between levels) and global-salient (i.e., the local letters are small, which should engender less conflict between levels) versions of the traditional Navon letters. Here, participants were always asked to attend to the global level of the hierarchical stimulus. We expected that there would be more competition when information from the competing local level is more salient than the information from the response (i.e., global) level. Thus, people who attend to the local-salient stimuli should experience more conflict and demonstrate larger congruency effects, which signals an increased demand for selective attention, and subsequently solve more problems analytically. Conversely, there is less competition when information from the global (i.e., response) level is more salient than information from the local level. As a result, we should expect that people who attend to the global-salient stimuli should experience less conflict and demonstrate smaller congruency effects (i.e., does not demand as much selective attention) compared to people who attended to local-salient stimuli, and they would demonstrate either no increase or a smaller increase in subsequent analytic solving.

### 2.5.2 Study 2 Methods

**Participants.** Seventy-three people (40 females, mean age = 18.85) participated in this study for partial course credit. Data from six participants were excluded from the final analysis due to poor CRA solving performance (see related outlier analysis). Data from one participant were excluded from the final analysis due to poor performance on the Global letter task (performance was at chance level). Data from four participants were excluded from the final analysis for not using the insight and analysis ratings (i.e., only used insight or only used analysis). Finally, data from six participants were excluded from the final analysis for having recently participated in another experiment that used the same CRA problems. (People tend to solve problems they have previously solved by recalling the solution instead of using problem solving processes; Jacoby, 1978.) Ultimately, data from 56 participants (32 females; average age = 18.90 years) were analyzed, belonging to one of two test conditions: The Global-Salient condition ($n$ = 28, 13 females; average age = 18.41 years) or the Local-Salient condition ($n$ = 28, 19 females, average age = 18.71 years). All participants consented to participate in the study, which was approved by the Northwestern University Institutional Review Board.

**Procedure.** Participants were instructed on how to solve CRA problems (see Figure 2 and 2.1.1. Study 1a Methods for a complete description of the CRA procedure), and then attempted a set of three practice problems. If participants did not solve any of the three practice problems, they attempted another set of three practice problems. Participants had 12 seconds to solve each CRA problem, during which they were asked to come up with a solution word that can be combined with each of the three problem words to form a common compound word or phrase. If the participant reached a solution, they gave their solution aloud to the experimenter and then were asked to indicate how they solved the problem: with insight or with analysis. If the participant did not solve the problem, they would proceed to the next problem. Then, participants attempted a baseline set of 50 CRA problems. Participants did not receive any feedback while attempting any of the CRA problems. After completing the baseline set of CRA problems, participants performed either the Local-Salient or Global-Salient version of the Global Letter task from Study 1 (see Figure 3 and 2.1.1. Study 1a Methods for a general description of Global version of the local-global letter task procedure). Participants completed 10 practice trials, and they received feedback after each trial. Then, participants performed 160 trials of the letter task without feedback. Participants attempted another 25 CRA problems, performed another 160 trials of the Global Letter task (to reinduce the attentional state), and attempted the final 25 CRA problems. The two sets of 50 CRAs were counterbalanced for difficulty and average insight and analytic ratings based on norms from previous experiments from our lab. The experiment was programmed in PsychoPy (Peirce, 2007).

**Global Letter Task.** Participants performed either the Local-Salient or Global-Salient versions of the Global Letter Task described in Study 1. In both versions, participants were seated at a chinrest 59 cm from the screen, and were asked to judge whether the global (large) letter was an H or S by pressing a left (was an H or S) or right (was not an H or S) button on a keyboard. Participants received the same instructions as in the Global letter condition in Study 1. All stimuli were presented in the center of the display against an achromatic gray background.

In the Local-Salient version of the Global letter task, the local letters were large and prominent to make the local level appear more salient or more difficult to ignore, thus inducing more conflict (see Appendix for examples of the stimuli). The global letters in the Local-Salient version subtended visual angles ranging from 7.54° vertically x 2.51° horizontally to 7.54° vertically x 7.54° horizontally. The local letters in the Local-Salient version subtended visual angles ranging from 1.23° vertically x .41° horizontally to 1.23° vertically x 1.23° horizontally. Additionally, the edges of Local-Salient stimuli were purposefully misaligned to create a stronger illusion of local salience and poorer "global goodness".

In the Global-Salient version of the Global letter task, the local letters were small but still legible and the edges were aligned (i.e., good "global goodness"), thus making the global letter appear more salient. The global letters in the Global-Salient version subtended visual angles ranging from 4.62° vertically x 1.54° horizontally to 4.62° vertically x 4.62 horizontally. The local letters in the Global-Salient version subtended visual angles ranging from .32° vertically x .11° horizontally to .32° vertically x .32° horizontally.

### 2.5.3 Study 2 Results

**Data Analysis.** Given the overall high (i.e., near ceiling) performance on the Global letter task, we chose to define outliers as accuracy below three standard deviations from the mean (*M* = 96.74%, *SD* = 6.06%). Only data from one participant (whose performance was at chance) fell below 78.56% and was not included in the final analysis. Mean Global letter task performance was 97.40% (*SD* = 2.63%) after removing the outlier.

Box plots were drawn to determine outliers in CRA solving performance (i.e., the proportion of correct solutions to the total number of CRA attempts). Data from six participants whose performance fell under 64.10% were considered extreme outliers (Figure 7). Mean CRA solving performance was 90.97% (*SD* = 8.80%) after removing the outliers.

Shapiro-Wilk tests determined that congruency effects (i.e., difference in latency between incongruent and congruent trials) from the Global letter task and CRA solving data (i.e., number of correct, insight, and analytic solutions) are normally distributed. All further analyses utilizing congruency effects and CRA data were performed with parametric tests. All analyses in this study, including the normality and outlier tests described here, were performed in R.

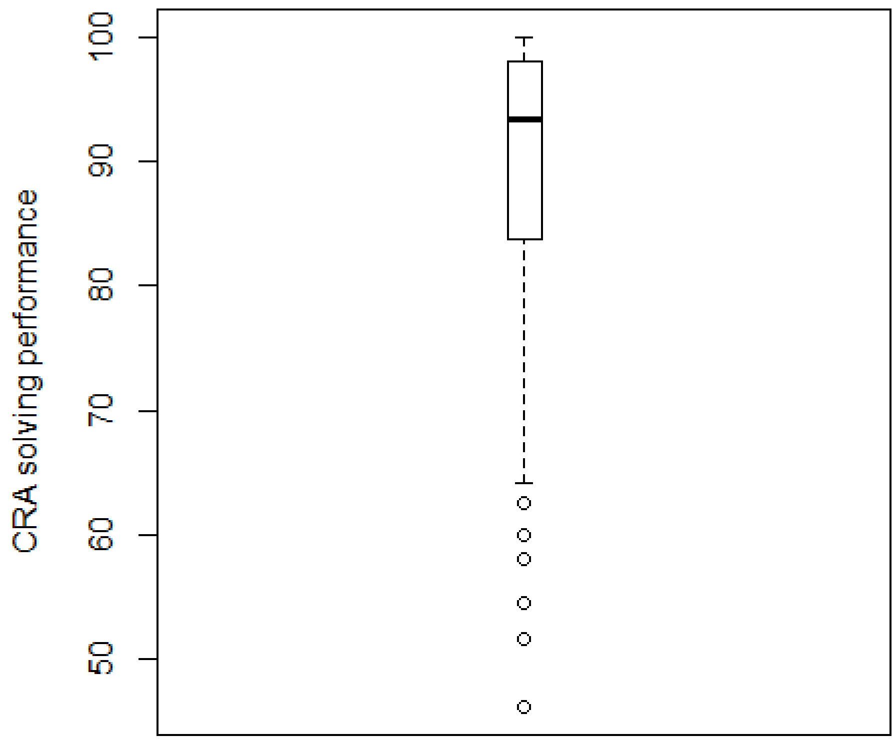


*Figure 7.* Box plot of CRA solving performance in Study 2. Data from six participants whose performance fell under 64.10% were considered outliers on the CRA task.

**Global-Salient and Local-Salient Task Performance.** On average, participants in both conditions performed near ceiling on both inductions of the Global Letter task (Table 4). There was no reliable difference between Global-Salient and Local-Salient conditions on the number of correct responses on the first induction, $t(54) =. 28$, $p > .05$, nor on the second induction, $t(54) = .68$, $p > .05$, of the Global letter task. Additionally, neither participants who judged global-salient targets, $t(27) = .62$, $p = .54$, nor those who judged local-salient targets, $t(27) = .22$, $p = .83$, improved in their accuracy between the first and the second inductions.

Participants who judged the local-salient targets were, on average, reliably slower than those who judged the global-salient targets on the first induction, $t(54) = 2.08$, $p = .04$, but not on the second induction of the Global letter task, $t(54) = .39$, $p = .69$. However, there were no reliable changes in average latencies from the first to the second inductions in neither the Global-Salient, $t(27) = .70$, $p = .49$, nor Local-Salient conditions, $t(27) = 1.86$, $p = .08$

**Congruency Effects.** In general, participants in both conditions responded more quickly on trials where the letters were congruent at both levels than when they were incongruent in the first induction, $F(1,53) = 4.65$, $p = .01$, $\eta_p^2 = .04$, and in the second induction, $F(1,53) = 4.05$, $p = .05$, $\eta_p^2 = .04$, of the Global letter task. Congruency effects were also reliably larger in Local-Salient compared to the Global-Salient condition, $F(1, 53) = 8.46$, $p < .01$, $\eta_p^2 = .04$, but they did not differ in the reinduction, $F(1,53) = .29$, $p = .59$ (most likely because participants numerically improved their performance in the Local-Salient condition). Thus, as predicted, participants who judged local-salient stimuli (i.e., had more conflict) demonstrated larger congruency effects, suggesting that the local-salient version of the task demanded more selective attention compared to participants who judged global-salient stimuli, which had less conflict (Table 5).

Table 4

*Global Letter Task Performance in Study 2*

| | First Induction | | Second Induction | |
|---|---|---|---|---|
| Global Letter Task Condition | % Correct | Mean latency | % Correct | Mean latency |
| Global-Salient (*n* = 28) | 97.30% (3.19%) | 572.90 ms (61.14 ms) | 97.46% (2.57%) | 584.50 ms (75.18 ms) |
| Local-Salient (*n* = 28) | 97.50% (1.98%) | 610.27 ms (73.51 ms) | 96.43% (9.29%) | 577.11 ms (64.46 ms) |

Note: Mean (and SD) percent of trials with correct responses and corresponding latencies for global-salient and local-salient conditions in Study 2.

Table 5

*Congruency Effects for the Global Letter Task in Study 2*

| Global Letter Task Condition | First Induction Congruency Effect (ms) | Second Induction Congruency Effect (ms) |
|---|---|---|
| Global-Salient (*n* = 28) | 14.43 (25.41) | 23.84 (25.46) |
| Local-Salient (*n* = 28) | 41.01 (20.85) | 31.07 (46.35) |

Note: Mean (and SD) congruency effects in ms (latencies of incongruent – latencies of congruent trials) for global-salient and local-salient conditions in Study 2.

**CRA Performance.** As in Study 1, CRA solutions made within 2 seconds were considered "fast recognition" solutions, and they were not included in the final analyses. On average, overall solving rates for both Global-Salient ($M$ = 18.39, $SD$ = 9.63) and Local-Salient ($M$ = 18.64, $SD$ = 7.37) conditions were not reliably different at baseline, $t(54) = .14$, $p = .89$. Average insight ratings for both conditions (Table 6) were not reliably different at baseline, $t(54) = .54$, $p > .59$. Average analytic ratings for both conditions (Table 6) were also not reliably different at baseline $t(54) = .28$, $p = .78$.

We examined changes in insight and analytic problem solving for each attention condition using mixed-measures 2 (solution type: insight vs analysis) x 2 (time: pre vs post) ANOVAs. The interaction between solution type and time in the Global-Salient condition was not reliable, $F(1,24) = .03$, $p = .87$. There were also no reliable main effects of solution type or time. A planned one-tailed pairwise t-test comparing the number of analytic solutions at baseline to after the global-salient version of the Global letter task was not quite reliable, $t(27) = .48$, $p = .32$.

The interaction between solution type (i.e., insight vs analysis) and time (i.e., pre vs post) in the Local-Salient condition was not reliable, $F(1,24) = .02$, $p = .89$. There were also no reliable main effects of solution type or time. A planned one-tailed t-test revealed that analytic solving reliable increased after participants judged local-salient stimuli, $t(27) = 1.75$, $p = .04$, $d = .28$. Thus, as predicted, attending to a visual stimulus with a greater degree of conflicting information induces an attentional state conducive to analytic solving.

Table 6

*Change in Insight and Analytic Solutions of Compound Remote Associates (CRA) Problems in Study 2*

| | Before Letter Task Manipulation | | After Letter Task Manipulation | | Change (After – Before) | |
|---|---|---|---|---|---|---|
| Global Letter Task Condition | Insight | Analysis | Insight | Analysis | Insight | Analysis |
| Global-Salient ($n$ = 28) | 9.07 (5.52) | 8.96 (4.48) | 9.89 (6.74) | 9.43 (6.11) | 0.82 | 0.47 |
| Local-Salient ($n$ = 28) | 8.36 (4.33) | 9.29 (4.12) | 9.21 (4.43) | 10.36 (3.64) | 0.85 | 1.07* |

*$p < .05$, one-tailed t-test

Notes: Mean (and SD) correct number of solutions reported as insight or analysis in each Global letter task condition in Study 2.

### 2.5.4 Study 2 General Discussion

Across two studies and three experiments, we have demonstrated that 1) people have more selective attention when they attend to stimuli that contain information that compete across levels of visual processing, and 2) they tend to solve more verbal problems with analysis after performing a visual attention task that increases selective attention. Specifically, we found that attention to the global level of a hierarchical letter stimulus required more selective attention (indexed by larger congruency effects), particularly when the local level was a different letter (i.e., incongruent) and when the features comprising the local level were more visually salient than the global level. Additionally, in both studies, the size of the congruency effects in the conditions with more conflict (i.e., Global condition in Study 1, and local-salient condition in Study 2) were consistently larger (and by at least 20 ms) compared to the conditions with less conflict (i.e., local condition in Study 1, and Global-Salient condition in Study 2). In line with similar studies (e.g., Wegbreit et al., 2012), these results putatively suggest that a more selective attentional state is conducive to analytic rather than insight solving, at least for verbal problems like the CRAs.

In this study, we found that asking participants to attend to and judge global letters with conflicting, locally-salient features demanded more selective attention (i.e., demonstrated larger congruency effects), which subsequently increased analytic problem solving. While this finding was reliable, it was also a weak (but almost moderate) effect. People who attended to global letters with global-salient features did not reliably increase analytic solving, which suggests that it is not simply attention to global stimuli that induces analytic solving; rather, the presence of salient conflicting information is pivotal in evoking a selective attentional state that is conducive to analytic solving. This explanation is in line with findings from Study 1 wherein we used global stimuli that were relatively balanced in the saliency of global and local components. That is, we found that attention to global letters in Study 1 demonstrated congruency effects more similar in magnitude to those elicited by the local-salient stimuli than those elicited by the global-salient stimuli in Study 2. Taken together, these results suggest that attention to conflicting information requires the engagement of more selective attention, which, in turn, facilitates analytic (but not insight) problem solving.

One explanation for the mechanism through which an attention task may influence subsequent problem solving may come from links between neural correlates of the traditional Navon letter task and analytic problem solving. Unfortunately, there are few studies on analysis within a creative problem solving context since most studies on this area of interest do not distinguish insight and analytic solutions, or they consider all solutions of "insight" problems to be insightful. However, mathematical problem solving is similar to analytic problem solving such that it also often involves a deliberate, conscious, and step-by-step solving process. Attention to the global level of information while ignoring conflicting information from the local level increases activity in areas involved in conflict monitoring such as the ACC (Weissman, Giesbrecht, Song, Mangun, & Woldorff, 2003; Weissman, Gopalakrishnan, Hazlett, & Woldorff, 2005), which subsequently increases neural activity in the prefrontal cortex (PFC; Kerns, 2004). The PFC is involved in the ability to selectively attend through sensory gating (Chao & Knight, 1995) as well as working memory processes involved in attentional control (Kane & Engle, 2003). Mathematical problems engage similar brain areas during solution. People showed greater activity around the fontal gyri and dorsal lateral PFC (i.e., areas involved in working memory and executive control) and right precuneus (i.e., involved in selective attention) during the solution of algebraic problems (Lee et al., 2007; Liang et al., 2014). Thus, is possible that engaging in an attention task with conflicting information engages similar neural correlates as those involved in analytic problem solving, thus priming the system to engage in analysis during subsequent tasks.

Finally, we have not yet reliably or consistently manipulated attention to be in a *less* selective state that may be conducive to insight solving. In the following studies, we used an ensemble statistics task that appears to require less selective attention to induce insight solving. And, we investigated whether people who are better able to distribute their attention across time, as measured by the ability to avoid an attentional phenomenon known as attentional blink, also tend to be insight solvers.

# Chapter 3: The Effects of Inducing Distributed Attention on Subsequent Problem Solving

## 3.1 Study 3 Introduction

In Studies 1 and 2, people increased analytic, but not insight, problem solving on Compound Remote Associates (CRA) problems after attending to the global level of hierarchical letter stimuli (i.e., Navon letters) than at baseline. When attending to the global stimulus, people need to suppress or inhibit representation of local stimuli, suggesting that attention to the global level demands attentional selectivity. Indeed, we found that people who attended to the global level demonstrated greater congruency effects, an index of selective attention, compared to people who attended to the local level. Neuroimaging studies also support the idea that attention to the global level of information requires selective attention: The dorsal anterior cingulate (dACC), which is involved in conflict monitoring, showed greater neural activity when people attended to the global level while inhibiting distractors at the local level and vice versa (Weissman et al., 2003); Weissman et al., 2005). This suggests that attention to either level of information generates conflict, which activates the dACC and signals prefrontal areas to increase selective attention toward the cued hierarchical level. Additionally, people showed greater neural activity in conflict monitoring areas, including the left ACC and medial prefrontal cortex, when attending to incongruent global stimuli, suggesting that interference from the local level elicited conflict (Hechtman, 2015). Thus, attention to the global hierarchical stimuli induces more selective attention, even if the task also requires attention to become spatially broadened (i.e., to see the whole global letter), which benefits analytic solving.

Previous experiments suggest that insight problem solving may require attention that is less selective or weakly distributed (e.g., Ansburg & Hill, 2003; Wegbreit et al., 2012).

Distributed attention refers to the allocation of less selective attention across a display and across multiple items or features (e.g., Treisman, 2006). That is, fewer objects, features, or events are being ignored or filtered from awareness compared to when attention is more selective, allowing one to "take in" more information at a lower resolution (see Figure 1). In a study by Wegbreit and colleagues (2012), participants identified an animal that was presented for 40 ms and subsequently masked. The authors posited that this rapid object identification task requires less selective attention to the quickly presented stimuli, which may encourage attention to weakly activated internal representations and subsequently benefits insight solving. A slightly different interpretation is that the rapid object identification task may require distributed attention that allows one to quickly extract gist information, which could also encourage the detection of weakly activated internal representations. Support for this interpretation comes from a study investigating a similar attentional paradigm. Here, people detected the presence of an animal in a natural scene that was presented for 32ms and subsequently masked (Brand & Johnson, 2018). While people performed the detection task, they also identified the orientation of a large rectangle surrounding the scene (i.e., encouraging or inducing distributed attention) or a small rectangle in the center of the scene (i.e., encouraging or inducing focused attention). People were reliably more accurate at detecting an animal, and did so reliably quicker, when they performed the distributed attention task (i.e., large rectangle) than the focused attention task (Brand & Johnson, 2018). The results suggest that distributed attention facilitates object perception even when people are provided a minimal amount of information. In other words, people are better at extracting the gist or summary statistics from rapidly presented information when their attention is less selective and diffusely distributed across a display.

Distributed attention is also central to other tasks used to study attentional processes, particularly those involving ensemble or summary statistics, which involves the extraction of average information in a display (e.g., Alvarez & Oliva, 2009; Alvarez, 2011). The ability to distribute attention is why people can more accurately report the average size of a set of objects than a single object from the same set (Ariely, 2001). In addition, the ability to average a large number of items can be enhanced by encouraging or modulating distributed attention (e.g., Chong & Treisman, 2005). Distributed attention also plays an important role in the perception of global motion of a set of randomly moving dots, whereas focused attention seems to benefit the perception of local coherent motion (e.g., Watamaniuk & Sekuler, 1992). The perception of visual "pop outs" in a crowded scene also benefits from distributed attention to the whole display (Treisman, 1991). Distributed attention may be more beneficial to ensemble statistics tasks (as well as global motion and "pop out" tasks) because attention to the average of multiple noisy representations is more accurate than focused attention to a single noisy representation (Alvarez, 2011; Figure 1). In other words, when attention is distributed diffusely, representation of the display is noisy and coarsely coded, which may make it easier to detect a unique target (e.g., in a "pop out" visual search) or to access more global information (e.g., in a coherent motion task).

A distributed state of visual attention, wherein attention is less selective and weakly dispersed across a display, may be analogous to a less selective state of conceptual attention that is conducive to insight problem solving. Conceptual space can consist of strongly-activated dominant semantic associations and weakly-activated remote semantic associations. When attention is distributed across conceptual space (parallel to visual space), weak associations may have a greater opportunity to capture attention (Kounios & Beeman, 2014). This process, which is largely unconscious, may result in an insight experience when the non-dominant but ultimately correct answer is detected and "pops" into conscious awareness. However, if attention is too selective, our unconscious search processes may be too narrowly focused on dominant or incorrect semantic associations. As we have observed in previous experiments, more selective attention is conducive to analytic, but not insight, solving, while less selective attention is conducive to insight solving. Moreover, we can induce these attentional states using visual attention tasks, such as central flanker tasks (i.e., induces more selective attention) or a rapid object identification task (i.e., induces less selective attention) (Wegbreit et al., 2012). Thus, if there is a real connection between distributed visual attention and distributed conceptual attention, we should expect that performing a visual attention task that demands a distributed attentional state, such as an ensemble statistics task, should induce less selective conceptual attention conducive to insight problem solving.

To test this idea, participants solved CRA problems, which provides a measure of insight and analytic solving, and performed one of two versions of an ensemble statistics task (adapted from Chong & Treisman, 2005). In one version of the ensemble statistics task, participants judged the average size of all of the objects (i.e., variously-sized closed circles) in the display. We expected that this version of the ensemble statistics task should require distributed (or less selective) attention, which should increase subsequent insight solving. Some preliminary evidence from our lab supports the idea that a task that induces a state of distributed attention could be conducive to insight solving. Specifically, the data showed that insight solving increases numerically after manipulating attention with a global motion task, which should involve distributed attention. While this finding was not statistically reliable, the insight solving increased in the predicted direction despite having a relatively small sample size (*n* = 20) and is encouraging. In another version of the ensemble statistics task, other participants judged the size of the circle that appeared in the center of the display (which again consisted of numerous variously-sized circles) while ignoring all other circles. We predicted that this task would demand more selective attention, which should increase subsequent analytic solving.

### 3.2 Study 3 Methods

**Participants.** Eighty people (48 females, mean age = 18.63) participated in this study for partial course credit. Participants were randomly assigned to either the Mean Size (26 females, mean age = 18.50) or Central Circle (22 females, mean age = 18.75) group, which determined which version of the ensemble statistics task they would perform during the experiment. Data from three participants were excluded from the final analyses for being outliers (i.e., mean discrimination thresholds were higher than the maximum in box plots) in either version of the first induction of the ensemble statistics task. Data from three participants were excluded from the final analyses due to poor solving performance on the CRA task (i.e., the percent of correct solutions out of total solving attempts) as determined by outlier analyses. Additionally, data from two participants were excluded from the final analyses for not using either the insight or analytic ratings (i.e., used only insight or used only analysis). (Data from two participants were considered outliers in the reinduction of the Central Circle version of this task, but their data were already excluded because they were also outliers on either the first induction or the CRA task.) The final analyses were comprised of data from 72 participants (41 females, mean age = 18.67).

All participants were native English speakers and consented to participate in the study, which was approved by the Northwestern University Institutional Review Board.

**Materials and procedure overview.** First, participants attempted a baseline set of 50 CRA problems. The CRA task parameters and procedure were the same as described in Studies 1 and 2 (see Figure 2). Participants had 12 seconds to come up with a solution word (e.g., APPLE) that can be combined with each of three problem words (e.g., PINE—CRAB—SAUCE) to form a common compound word or phrase. Participants also reported whether they solved the problem with insight or analysis. There were two sets of CRA problems, which were counterbalanced across all participants and conditions. Then, participants performed one of two versions (i.e., Mean Size or Central Circle) of the visual ensemble statistics task to induce either a distributed or selective attentional state, respectively (see Figure 8). After the ensemble statistics task, participants attempted another 25 CRA problems, and then they performed a shorter version of the visual ensemble statistics task again to reinduce either a distributed or selective attentional state. Finally, participants attempted the final set of 25 CRA problems. Participants were seated 59 cm from the screen for all tasks, and the study was approximately one hour long.

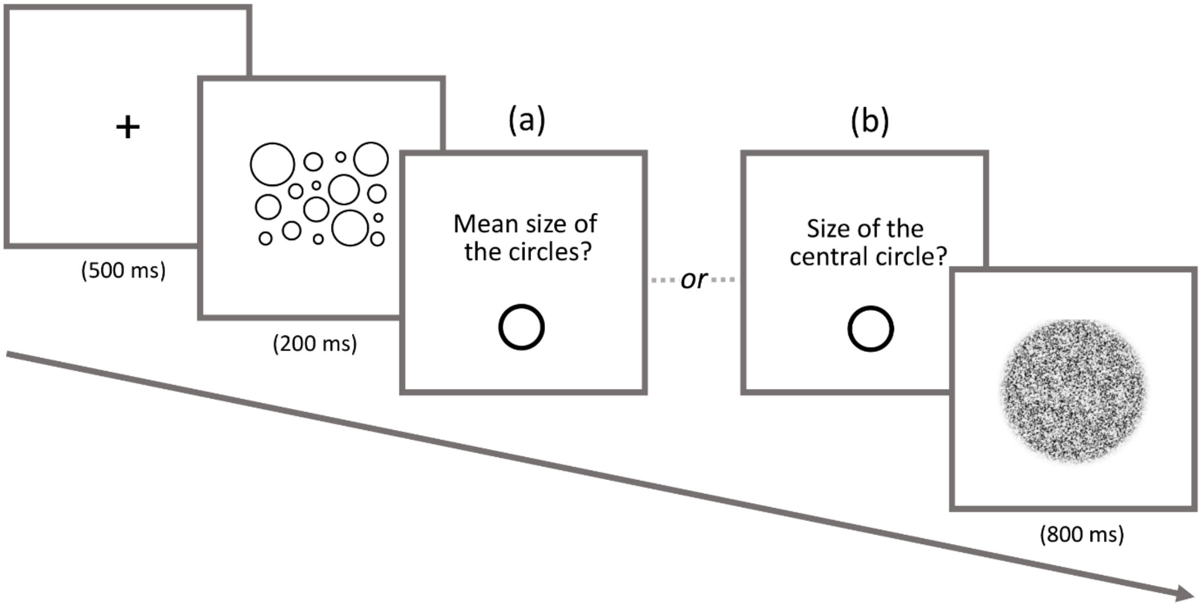


*Figure 8.* Schemata of the ensemble statistics task. Participants were asked to either (a) judge whether the mean size of the quickly-presented (200 ms) display of 16 variously-sized circles was larger or smaller than a target circle, or (b) judge whether the size of the circle in the center of the same display (as marked by a previously-presented fixation cross) was larger or smaller than a target circle. Participants were given as much as time as needed to perform the size judgment. At the end of each trial, participants viewed a static patch for 800 ms to mask any residual visual information before the next trial.

**Ensemble statistics task.** Participants performed one of two versions (i.e., Mean Size or Central Circle) of the ensemble statistics task (see Figure 8). The basic paradigm for this task was adapted from Chong and Treisman (2005). In both versions of the task, participants saw a fixation cross and heard a short auditory beep (i.e., $G_4$) for 500 ms. A display of 16 variously sized closed circles was presented for 200 ms. All stimuli were presented against an achromatic gray background. The closed circles had black outlines and the inside of the circles was the same color as the background. Each of the 16 circles were randomly placed into one of 25 imaginary cells in an invisible 5 x 5 matrix (i.e., participants could not see the grid). In the Central Circle version of the task, one of the 16 circles always appeared in the center of the display, which was marked by the preceding fixation cross. Each cell in the matrix subtended a visual angle of 2.91° (length) x 2.91° (width), and the maximum area of the circle display was 14.49° (length) x 14.49° (width). There were four sets of 16 predetermined circle sizes, which were scaled by a multiplicative factor (i.e., 1, 1.1, 1.2, and 1.3) to prevent participants from basing their judgments on previous displays of circles. Within each of the four sets, the size of each individual circle was equally spaced on a log scale separated by a factor of 1.15. The mean diameter of all circles was 1.42°, and the diameters ranged from 1.03° to 2.85°.

After the quick presentation of the circle display, participants were asked to make size judgments about a test circle. In the Mean Size version of the ensemble statistics task, participants judged whether the size of the test circle was larger or smaller than the average size of 16 circles in the previous circle display. In the Central Circle version of the ensemble statistics task, participants judged whether the size of the test circle was larger or smaller than the circle that appeared in the center of the display. The center of the display was marked by the fixation that preceded the circle display. In both versions of the task, the test circle remained on the screen until a judgment was made. Participants pressed left button (“F” key on the keyboard) if the test circle was larger the target size, and they pressed right button (“J” key on the keyboard) if the test circle was smaller than the target size. Participants received auditory feedback (i.e., $A_4$ played for 500 ms) after incorrect judgments, but they did not hear any beeps if their response was correct. Prior to the next trial, participants saw a static patch for 800 ms to mask any residual visual artifacts from the previous display.

As in the original study, we utilized a 3-down 1-up staircase procedure to determine each participant’s judgment threshold. The size of the test circle was adjusted to achieve 80% accuracy on the task. On any given trial, the test circle was either larger or smaller than the target size (i.e., mean or central circle). Whether the test circle was larger or smaller than the target size was randomized each trial. The starting size of the test circle (i.e., on the first trial of either version of the ensemble statistics task) was always 25% larger or smaller than either the mean size of all circles (i.e., if Mean Size version) or central circle (i.e., if Central Circle version) of the previous circle display. When participants made three correct size judgments in a row, the difference between the test circle and the actual size of the circle decreased by 3%. When participants made an incorrect size judgment, the difference between the test circle and the actual size of the circle increased by 3%. The maximum possible size difference between the test circle and target size was 50% (i.e., the test circle could be 50% larger or smaller than the target size). The minimum possible size difference between the test circle and target size was 1% (i.e., the test circle could be 1% larger than or smaller than the target size).

Participants first performed a practice block of 11 trials or 2 reversals, whichever came first. Then, participants performed the experimental block of the ensemble statistics task, which ended after 13 reversals or 120 trials, whichever came first. The reinduction of the ensemble statistics task, which participants performed after they attempted 25 post-induction CRA problems, ended after 7 reversals or 60 trials, whichever came first. We constrained the maximum number of trials for the ensemble statistics task to ensure that participants could complete the entire experiment, including the baseline and post-induction sets of CRAs, within an hour.

### 3.3 Study 3 Results

**Data analyses.** For the first induction of the Mean Size and Central Circle versions of the ensemble statistics task, mean discrimination thresholds were calculated by taking the average of the last 12 reversals of the staircase. For the reinduction for both versions of the ensemble statistics task, mean discrimination thresholds were calculated by taking the average of the last 6 reversals of the staircase. We created box plots to determine outliers on mean discrimination thresholds for the first and second inductions of the ensemble statistics task. Mean discrimination thresholds from two participants (thresholds over 22.50%) were considered extreme outliers in the first induction of the Mean Size version of the ensemble statistics task (Figure 9a), but no thresholds were considered outliers in the reinduction of this version of the task (Figure 9b). A mean discrimination threshold from one participant (threshold over 29.25%) was considered an extreme outlier in the first induction of the Central Circle version of the ensemble statistics task (Figure 9c), and thresholds from two participants (thresholds over 26.50%) were considered outliers in the reinduction of this version of the task (Figure 9d).

We used a box plot to determine outliers on CRA solving performance, which is the proportion of correct solutions compared to the number of total solving attempts made (Figure 11e). Data from three participants were considered extreme outliers (i.e., performance under 62.07%). With the outliers included, mean CRA solving performance was 88.33% (*SD* = 9.88%). After removing outliers, mean CRA solving performance was 89.58% (*SD* = 7.35%).

Shapiro-Wilk tests determined that the discrimination thresholds for the first and second inductions of the Central Circle (but not Mean Size) version of the ensemble statistics task are not normally distributed. Thus, any analyses utilizing these discrimination thresholds were performed with nonparametric tests. Shapiro-Wilk tests also determined that CRA solving data (i.e., number of correct, insight, and analytic solutions) are normally distributed, so all further analyses utilizing CRA data were performed with parametric tests. All analyses in this study, including the normality and outlier tests described here, were performed in R.

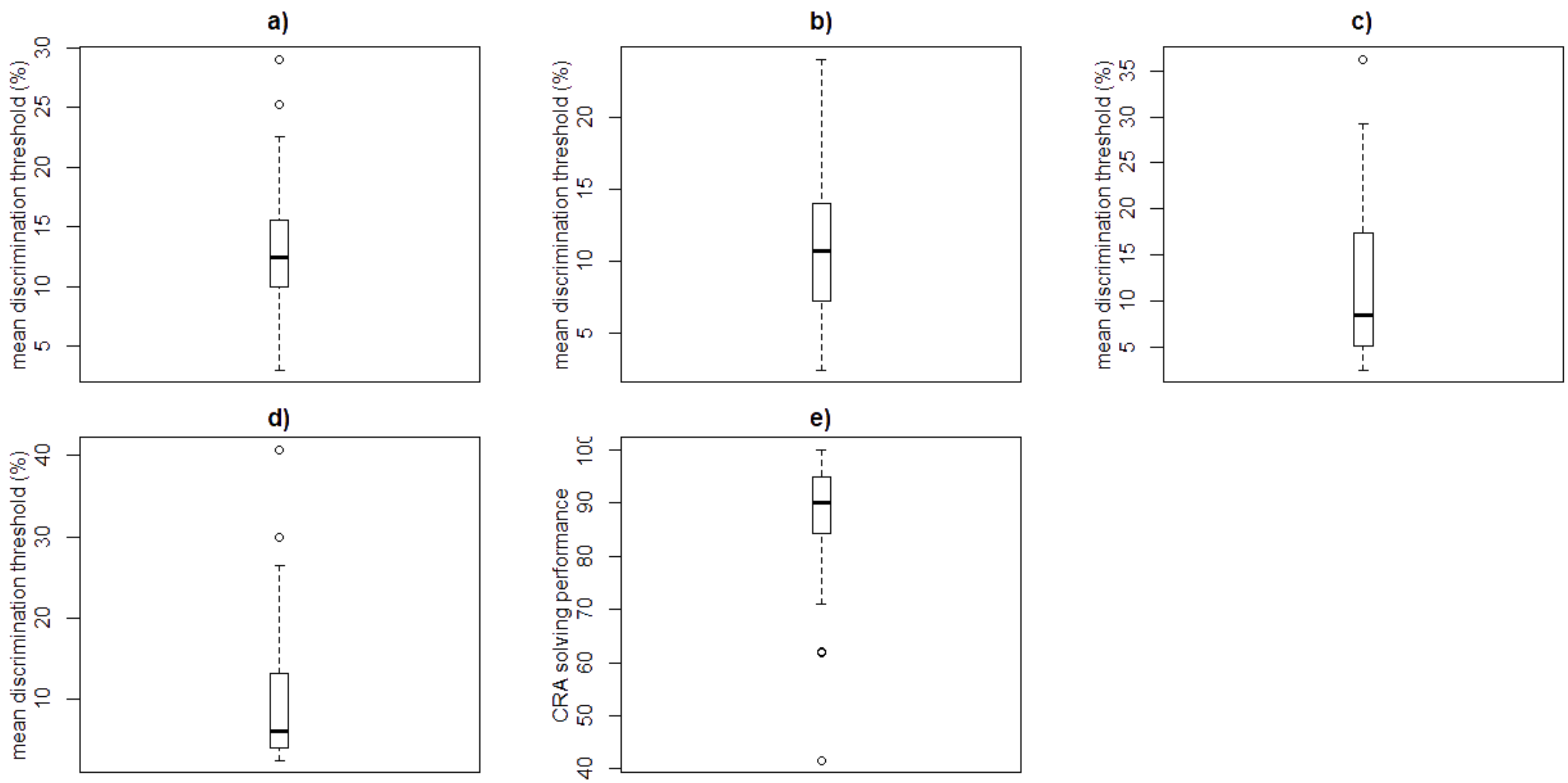


*Figure 9.* Box plots of mean discrimination thresholds and CRA solving performance in Study 3. a) Thresholds over 22.50% were considered outliers on the first induction of the Mean Size task. b) No data were considered outliers on the reinduction of the Mean Size task. c) Thresholds over 29.25% were considered outliers on the first induction of the Central Circle task. d) Thresholds over 26.50% were considered outliers on the reinduction of the Central Circle task. e) CRA solving performance under 62.07% were considered outliers.

**Ensemble statistics task performance.** The average mean discrimination threshold in the first induction of the Mean Size version, including outliers, was 13.09% (*SD* = 5.20%) and 11.23% (*SD* = 5.03%) in the reinduction. After removing outliers, the average mean discrimination threshold in the first induction of the Mean Size version was 12.34% (*SD* = 4.25%) and 11.23% (*SD* = 5.20%) in the reinduction. Mean discrimination thresholds ranged between 3.00% and 22.50% for the first induction of the Mean Size version and between 2.50% and 24.00% for the reinduction.

The average mean discrimination threshold in the first induction of the Central Circle version, including outliers, was 12.38% (*SD* = 8.89%) and 9.92% (*SD* = 8.66%) in the reinduction. After removing outliers, the average mean discrimination threshold in the first induction of the Central Circle version was 11.15% (*SD* = 7.85%) and 8.35% (*SD* = 6.43%) in the reinduction. Mean discrimination thresholds ranged between 2.50% and 29.25% for the first induction of the Central Circle version and between 2.50% and 26.50% for the reinduction.

A Scheirer-Ray-Hare test did not reveal a reliable interaction between the version of the ensemble statistics task and the time of induction ($p > .05$). However, there was a reliable main effect of ensemble statistics task version, $H(1,68) = 11.23$, $p < .01$, and a reliable main effect of time of induction, $H(1,68) = 4.66$, $p = .03$ (Figure 10). (A 2x2 ANOVA showed the same pattern of results as the Scheirer-Ray-Hare test.) Dunn's post-hoc tests with Bonferroni correction revealed that the average mean discrimination threshold in the Central Circle version of the ensemble statistics task was reliably lower than the average mean discrimination threshold in the Mean Size version ($p < .01$), which could suggest that the Central Circle task was easier than the Mean Size task. Additionally, on average, participants had a lower mean discrimination threshold in the reinduction than in the first induction ($p < .05$), suggesting that participants generally improved on the ensemble statistics tasks.

Planned comparisons (Wilcoxon Rank Sum tests) revealed that participants who performed the Mean Size version of the ensemble statistics task did not reliably change in their mean discrimination thresholds between the first and second induction ($p > .05$). However, participants who performed the Central Circle version reliably reduced their mean discrimination thresholds between the first and second inductions ($p = .01$), suggesting that they improved their performance in the reinduction of the task. (Paired t-tests showed the same pattern of results.)

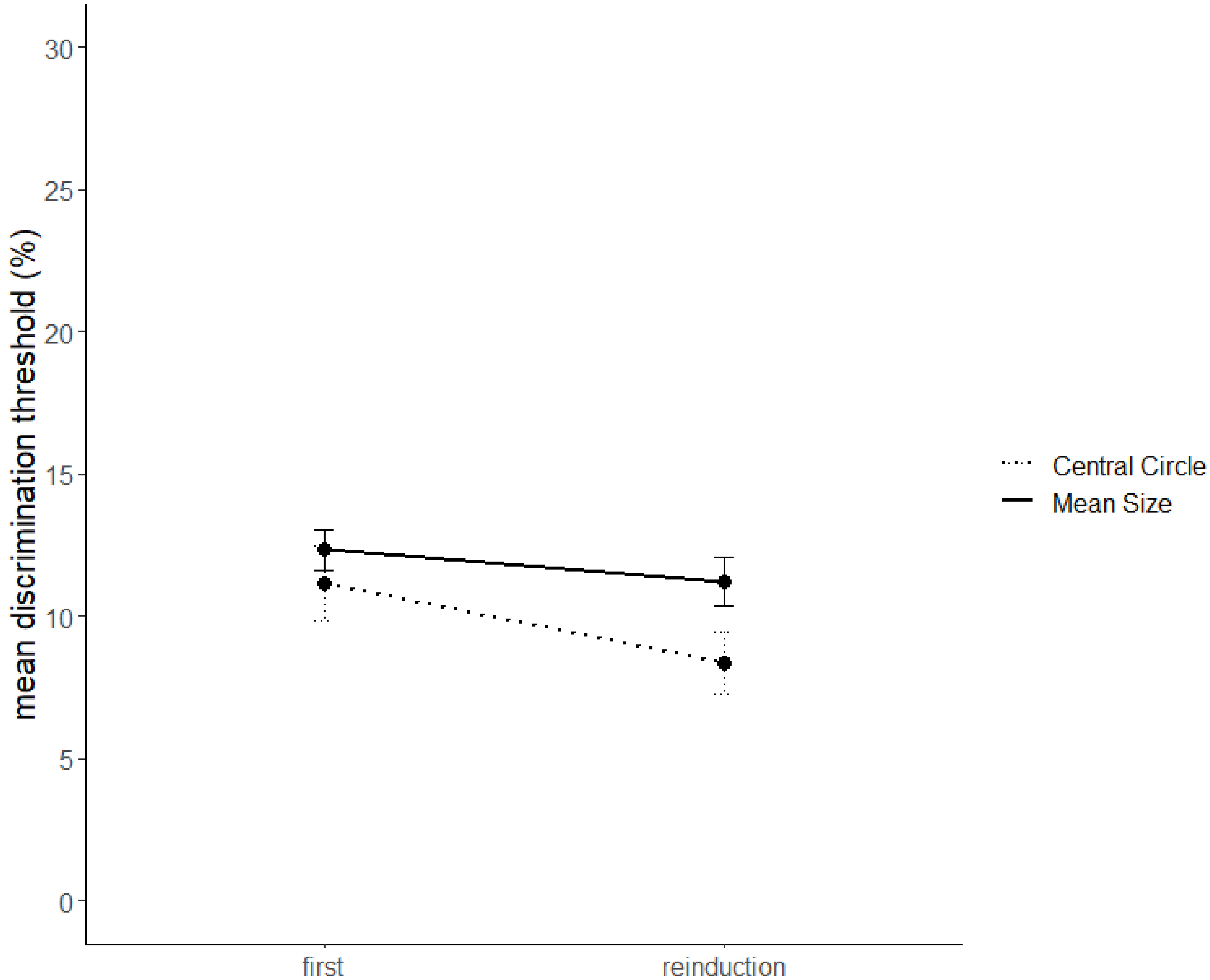


*Figure 10.* Change in mean discrimination thresholds between the first and second inductions of both versions of the ensemble statistics task.

**CRA performance.** There were no reliable differences in the number of correct, insight, or analytic solutions at baseline (all *p*'s > .05). In general, participants correctly solved 36.01% (*M* = 36.01, *SD* = 11.02) of the CRA problems. As in previous studies, we removed solutions considered "fast recognitions" (i.e., solutions given within a 2 second window) as they have different phenomenological and neural correlates compared to insight solutions. Fast recognitions constituted 1.69% (*M* = 0.56, *SD* = 1.03) of the total correct CRA solutions. Participants solved 54.57% (*M* = 19.65, *SD* = 11.01) of the CRA problems with insight, and 43.73% (*M* = 15.75, *SD* = 8.38) with analysis. [When considering outliers, participants correctly solved 36.15% of the CRA problems, 55.10% with insight, 42.79% with analysis, and 2.10% with fast recognition.]

A 2 (*ensemble statistics task version*: Mean Size vs Central Circle) x 2 (*time*: baseline vs post-ensemble statistics task) x 2 (*problem solving process*: insight vs analysis) ANOVA did not reveal a reliable three-way interaction (*p* > .05). The two-way interaction between version of ensemble statistics task and time was not reliable (*p* > .05) nor was the two-way interaction between time and problem solving process (*p* > .05). A two-way interaction between version of ensemble statistics task was marginally reliable, $F(1,67) = 3.27$, $p = .07$. There was a reliable main effect of problem solving process, $F(1,67) = 5.80$, $p = .02$, and a reliable main effect of time, $F(1,67) = 8.21$, $p < .01$. Tukey HSD post-hoc tests revealed that, overall, participants reliably solved more CRA problems with insight than with analysis ($p < .05$), and they solved more CRA problems after the ensemble statistics task compared to baseline ($p < .01$).

Planned comparisons (paired t-tests) compared the change in insight and analytic solving for both versions of the ensemble statistics task. We predicted that participants should increase in insight solving, but not analysis, after performing an ensemble statistics task that should require them to distribute attention across multiple objects (i.e., the Mean Size version) compared to baseline. Consistent with our prediction, we found that distributing attention across a spatial display facilitated subsequent insight solving compared to baseline, $t(35) = 2.76$, $p < .01$, $d = .46$, but distributing attention did not change subsequent analytic solving ($p > .05$). Moreover, participants tended to solve more CRA problems after the Mean Size version of the ensemble statistics task compared to baseline, $t(35) = 2.71$, $p = .01$, $d = .45$ (Table 7). We also predicted that participants should increase in analytic solving, but not insight, after performing a version of the ensemble statistics task that requires *selective* rather than *distributed* attention. While participants reliably solved more problems after performing the Central Circle version of the ensemble statistics task (Table 7), $t(35) = 3.46$, $p < .01$, $d = .58$, we did not find that performing this task, which may require more selective attention, facilitated subsequent analytic solving ($p > .05$) nor did it change insight solving ($p > .05$).

Table 7

*Change in Insight and Analytic Solutions of Compound Remote Associates (CRA) Problems in Study 3*

| | Total Correct Solutions | | Total Correct Insight Solutions | | Total Correct Analytic Solutions | |
|---|---|---|---|---|---|---|
| | Baseline | Post-EST | Baseline | Post-EST | Baseline | Post-EST |
| Mean Size ($n$ = 36) | 17.50 (6.25) | 19.69 (6.45) | 9.94 (5.36) | 11.78 * (6.39) | 7.42 (3.76) | 7.47 (5.09) |
| Central Circle ($n$ = 36) | 16.33 (5.11) | 18.50 ** (5.80) | 8.22 (5.45) | 9.36 (5.86) | 7.92 (3.94) | 8.69 (5.62) |

** $p < .01$, * $p = .01$

Note: For brevity, “ensemble statistics task” has been shortened to “EST”. Fast recognitions have been removed from insight and analysis. Standard deviations are represented in parentheses. The scores represent raw CRA solutions.

**Individual differences between discrimination thresholds and problem solving processes.** We also performed exploratory analyses examining individual differences between the ability to distribute attention or selective attend and the tendency to solve problems with either insight or analysis. Specifically, we looked at relationships between degrees of selective versus distributed (or less selective) attention and insight and analytic problem solving at baseline (i.e., prior to attentional manipulation, which should reveal any general tendencies to solve problems with insight or analysis).

Here, larger mean discrimination thresholds in the Mean Size version of the ensemble statistics task putatively signify a poorer ability to distribute attention across multiple objects in a visual display (or more selective attention). Conversely, smaller mean discrimination thresholds in the Mean Size version putatively signify that one was better able to distribute attention (or less selective attention). Thus, we might expect that smaller mean discrimination thresholds (i.e., more distributed attention) in the Mean Size version are related to more insight solutions or fewer analytic solutions at baseline. Likewise, larger mean discrimination thresholds in the Central Circle version of the ensemble statistics task putatively signify a poorer ability to selectively attend to the center circle (or more distributed attention) whereas smaller mean discrimination thresholds putatively signify better selective attention. Thus, we might expect that larger mean discrimination thresholds (i.e., less selective attention) in the Central Circle version should be related to more insight solutions or fewer analytic solutions.

Larger mean discrimination thresholds were weakly and negatively related to baseline insight problem solving ($r = -.12$, Figure 11a), but this correlation was not reliable ($p > .05$). There was no correlation between mean discrimination thresholds and analytic problem solving

(Figure 11b). Since discrimination thresholds in the Central Circle version of the ensemble statistics task were not normally distributed, we used Kendall's Rank Correlation tests to determine relationships between the ability (or inability) to selectively attend and problem solving. There was a reliable positive correlation between mean discrimination thresholds and insight solutions ($r_\tau = .25$, $p = .04$), which suggests that less selective attention (in the Central Circle version of the ensemble statistics task) is related to more baseline insight solving (Figure 11c). Finally, there was no relationship between mean discrimination thresholds in the Central Circle task and analytic solutions (Figure 11d).

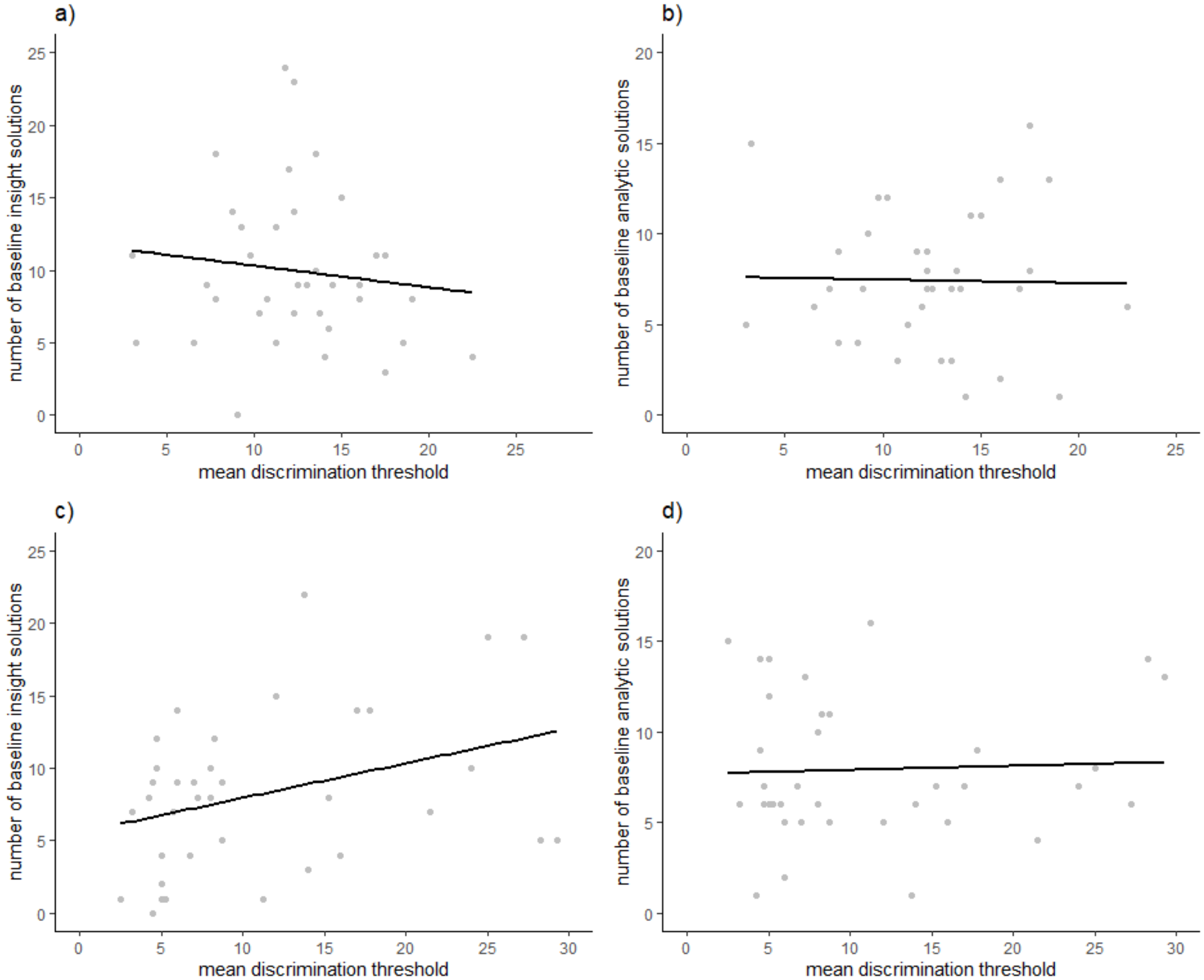


Figure 11. Correlations between mean discrimination thresholds and problem solving processes. a) Mean discrimination thresholds in the Mean Size version of the ensemble statistics task were weakly (but not reliably) negatively correlated with insight solutions at baseline. b) Mean discrimination thresholds in the Mean Size version of the ensemble statistics task were not correlated with analytic solutions at baseline. c) Mean discrimination thresholds in the Central Size version of the ensemble statistics task was positively correlated with insight solutions at baseline. d) Mean discrimination thresholds in the Central Size version of the ensemble statistics task were not correlated with analytic solutions at baseline.

**3.4 Study 3 Discussion**

In this study, we sought to test how performing a visual attention task that putatively requires distributed (or less selective) attention influences subsequent problem solving. Previous studies have shown that visual attention tasks can be used to induce more or less selective attention, and the attentional state induced by the visual attention task subsequently facilitates more analytic or insight solving, respectively (e.g., Wegbreit et al., 2012; see Studies 1 and 2). We chose to modulate visual attention with an ensemble statistics task, which is thought to require distributed attention or is at least improved by distributing attention (Chong & Treisman, 2005; Treisman, 2006; Whitney & Leib, 2018). We predicted that people who perform a version of the ensemble statistics task that encourages less selective or more distributed attention should subsequently solve more problems with insight (but not with analysis). As a contrast, we also designed a version of the ensemble statistics task that could require more selective attention rather than distributed attention. That is, we expected that paying attention to one object or feature (i.e., the size of the circle that appears in the center of the display) while ignoring all others (i.e., the size of the rest of the circles) should encourage more selective attention, which should facilitate subsequent analytic (but not insight) solving.

As in Studies 1 and 2, we observed that participants solved more verbal problems after the visual attention task. Even though the Central Circle version of the ensemble statistics task did not induce more analytic solving, it is possible that performing either version of this visual attention task has a small facilitatory effect on problem solving in general. It is also possible that the general increase in problem solving was due to a practice effect (i.e., generally getting better at solving the problems). However, regardless of why participants improved problem solving overall, our main interest was in how their problem solving processes (i.e., insight and analysis) changed as a result of performing one of the two versions of the ensemble statistics task.

In line with our first prediction, participants reliably solved more CRA problems and solved more problems with insight (without changing analytic solving) after they judged the average size of all the circles in the display compared to baseline. In other words, inducing a distributed attentional state via a visual attention task facilitates subsequent insight problem solving. This finding suggests that visual attention and conceptual attention could share a common underlying mechanism that enables attention to be either less selective or distributed (i.e., less or not focused) across a visual display and within conceptual space. In addition, given the modulatory effect of the ensemble statistics task, this shared attentional mechanism appears to be general and not specific to either visual or conceptual domains. However, this idea is still speculative and requires more research, particularly regarding the attentional processes underlying ensemble representations and summary statistics. There is a considerable dearth of research on the neural underpinnings of ensemble statistics or ensemble representations (Whitney & Leib, 2018), and most neuroimaging research regarding ensemble representations is focused on neural activity in areas typically involved in object or feature perception such as the parahippocampal place area (e.g., Cant & Xu, 2015). In addition, we did not have another attention task that could measure the degree to which attention was distributed or made less selective by the ensemble statistics task. While we cannot confirm that the ensemble statistics task necessarily induced more distributed attention, our findings extend the current research suggesting that less selective attention is conducive to insight.

Our second prediction, however, was not supported by this experiment; that is, participants reliably solved more CRA problems after judging the size of only the circle that appeared in the center of the display, but they did not change in either insight or analytic solving. One reason why this version of the ensemble statistics task did not induce more analytic solving is that attending to the central circle did not actually induce more selective attention. That is, participants may have not found it difficult to discriminate the size central circle from the sizes of the flanking circles. The relative ease of this task could be due to restricting the target circle to the center of the display where visual acuity is high. Since participants were fixated on the center of screen, they did not have to perform a visual search for the target, which would have made the task more difficult. The easiness of the task may also be due to the relative proximity (i.e., space between) surrounding circles; when the surrounding circles are spaced far apart from the central circle, there may be little need to engage selective attention because the surrounding circles do not create much conflict. This may be akin to incompatibility effects observed in central flanker tasks, which are generally larger (signaling more conflict) when close flanking letters are different from the central (i.e., target) letter when far flanking letters are different from the central letter (Zeef, Sonke, Kok, Buiten, & Kenemans, 1996). A future study could improve this version of the ensemble statistics task by making the display more crowded (i.e., adding more circles to the display), randomizing the location of the circle (i.e., requiring a visual search). Increasing the difficulty of this task may require participants to engage in more selective attention, which should be conducive to analytic problem solving.

Exploratory analyses also revealed potential relationships between individual differences in selective attention and the tendency to solve problems with insight. There was a reliable positive correlation between mean discrimination thresholds in the Central Circle version of the ensemble statistics task and insight solving. Specifically, less selective attention (i.e., poorer size discrimination of the central circle) was related to more insight solutions. In addition, there was a weak but not reliable negative correlation between mean discrimination thresholds in the Mean Size version of the ensemble statistics task and insight solving. These two findings provide some support for the idea that less selective (or more distributed) attention is related to an increased likelihood of solving problems with insight. However, there were no reliable correlations between analytic solving and either version of the ensemble statistics task.

In order to determine whether the effects of the ensemble statistics task are general to problem solving, future studies should attempt to replicate these findings with other types of problems that can also be solved with either insight or analysis (e.g., Rebus puzzles, anagrams). In addition, we do not know with certainty whether this task modulated attention to become less selective or more distributed; perhaps the Mean Size version of the ensemble statistics task could be used to manipulate attention in other visual attention tasks. For example, if this task requires less selective attention, it is possible that it may impair performance on a visual attention task that requires more selective attention (e.g., flanker task). Finally, methods to strengthen both versions of the ensemble statistics task should also be considered, particularly the version that should induce more selective attention. For example, Chong and Treisman (2005) were able to increase the distribution of attention, leading to better mean discrimination thresholds in their ensemble statistics task, by asking participants to identify the orientation of a large rectangle surrounding the circle display at the same time as making the average size judgement. In contrast, asking participants to identify a small rectangle in the middle of the display, thus reducing the distribution of attention (or increasing selective attention), was detrimental to performance on the ensemble statistics task.

In sum, the results of this research extend our findings from Studies 1 and 2. Specifically, while we found that *more* selective attention was conductive to analytic solving in Studies 1 and 2, *less* selective (or distributed) attention was conducive to insight solving in Study 3. The findings of this study also extend those of Wegbreit and colleagues (2012). In their study, the rapid object identification task was assumed to demand less selective attention, which subsequently increased insight solving. More recent studies suggest that the ability to discriminate rapidly presented scenes is related to sensitivity to ensemble statistics, which requires a distributed form of attention (Brand & Johnson, 2018; Shafer-Skelton, Brady, & Alvarez, 2014). Here, we found that performing an ensemble statistics task, particularly one that involves extracting mean information from a display, induces distributed attention and subsequently improves insight problem solving.

# Chapter 4: Individual Differences in the Attentional Blink and Insight and Analytic Problem Solving

## 4.1 Study 4 Introduction

In Studies 1, 2 and 3, we manipulated the selectivity of attention across visual features (i.e., the identity of letters at either global or local hierarchical levels in Studies 1 and 2) and the distribution of attention across several visual objects (i.e., summary statistics of variously-sized circles in Study 3) within a spatial domain, which subsequently modulated problem solving. Increased selective attention to the global level of visual information facilitated analytic solving, but it did not improve insight. Conversely, distributing attention across numerous objects (i.e., less selective attention) was beneficial for insight solving, but did not change analytic solving. Visual attention may also be selective or distributed across time, but its relationship with problem solving has yet to be investigated. This prompts an open question: Does selective or distributed attention in a temporal domain, like attention within a spatial domain, share common attentional mechanisms with insight and analytic problem solving?

When many similar events occur over a brief time, people may need to select one event over others. For instance, in a rapid serial visual presentation (RSVP) task, people are tasked with identifying two targets embedded within a stream of stimuli presented in quick succession. When the second target (T2) is presented within 150-500 milliseconds of the first target (T1), people are often unable to identify the second target, even though one is consciously fixated on the stimuli (Visser, Bischof, & Di Lollo, 1999). This phenomenon is known as an “attentional blink” (AB). The degree or magnitude of an AB is generally measured by calculating the decrement in accuracy when identifying T2 compared to T1 as a function of “lag”, or the position of T2 in the RSVP stream relative to T1. For example, T2 is said to be at “lag 1” if T2 appears immediately after T1, whereas T2 would be at “lag 2” if a distractor appears between T1 and T2. Typically, attentional blink is maximally present between lags 2 and 3 (see Figure 12, reprinted with permission from Taatgen, Juvina, Schipper, Borst, & Martens, 2009).

These blinks in attention may be explained by two general categories of hypotheses: an AB is either a result of limited attentional resources or an overinvestment of top-down attentional control (for a review, see Dux & Marois, 2009). Chun and Potter's (1995) *two-stage model* and Shapiro, Raymond, and Arnell's (1994) *interference theory* posit that attending to the first target (T1) consumes or “wins” more limited attentional resources during working memory consolidation, which leaves insufficient attentional resources to process T2. The processing of T2 must “wait” until resources become available, during which the representation of T2 becomes susceptible to interference from distractors, and its chances of reaching conscious awareness are reduced. Thus, attention “blinks,” and people are unable to report the identity of the second target.

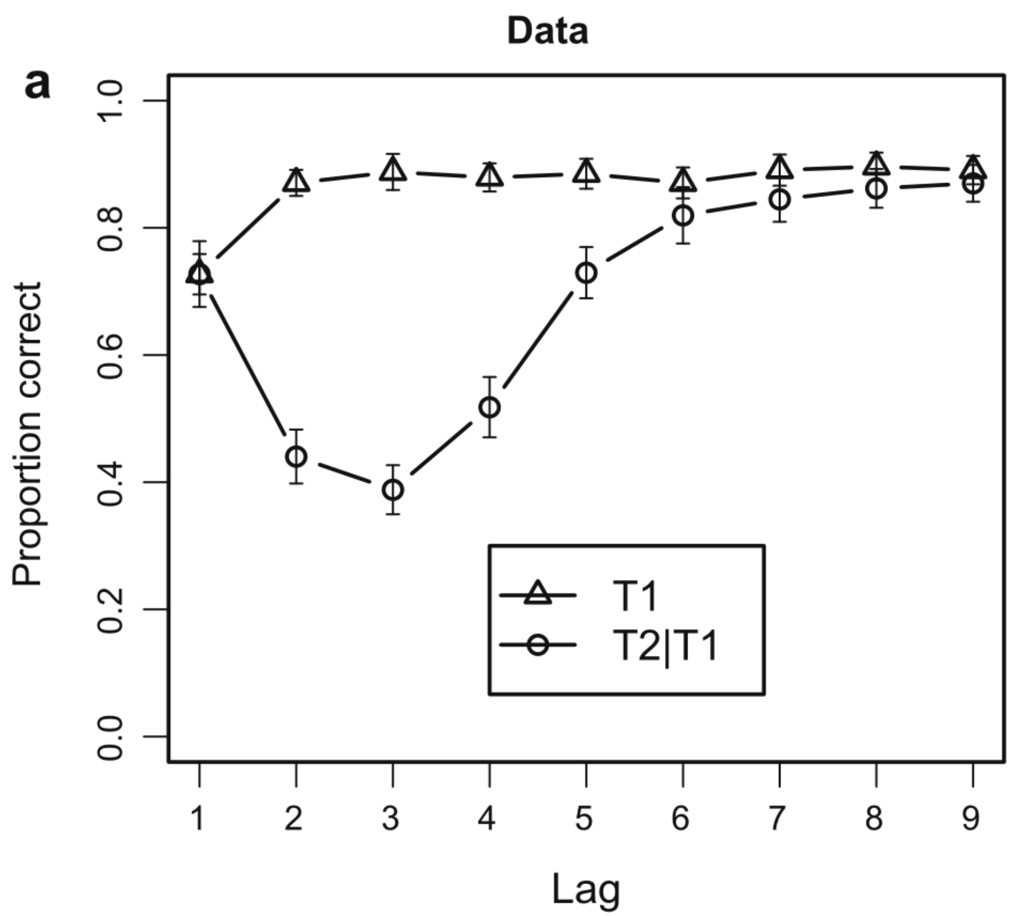


*Figure 12.* Typical attentional blink results. This graph exemplifies typical results from a standard rapid serial visual presentation (RSVP) task. The high accuracy of the second target (T2) given that the first target (T1) was reported correctly (T2|T1) at lag 1 (relative to lags 2-4) represents “lag-1 sparing”. The dips in accuracy at lags 2 and 3 represent attentional blinks. Recovery from attentional blinks, wherein people can report T2 as accurately as T1, generally occurs around lag 6 and higher. Reprinted from “Too much control can hurt: A threaded cognition model of the attentional blink”, by Taatgen, N. A., Juvina, I., Schipper, M., Jelmer, P., & Martens, S., 2009, *Cognitive Psychology, 59*(1), p. 7. Copyright 2011 by Elsevier. Adapted with permission.

Some AB-related phenomena present a challenge for limited resource theories. First, performing a dual task simultaneously with the RSVP task reduces rather than increases AB magnitude (Olivers & Nieuwenhuis, 2006). Limited resource theories would posit that adding another attention-demanding task should further reduce the amount of available resources for T2-processing, thereby increasing AB magnitude. Second, accuracy for identifying T2 increases when T2 appears at lag 1 (i.e., immediately succeeding T1), a phenomenon known as lag-1 sparing. Lag-1 sparing is challenging to limited resource models because T1 should still consume available resources, which would leave fewer resources for future items and reduce accuracy for T2. Newer theories, however, suggest that an overinvestment of top-down attentional control, rather than a resource bottleneck, is responsible for the attentional blink. These cognitive control models (i.e., *boost and bounce theory* and *threaded cognition model*) also provide better explanations for the occurrence of the full range of AB phenomena including dual task improvements and lag-1 sparing. Additionally, these models involve active, domain-general processes that connect both individual differences in AB magnitude and relationships with other processes that depend on the same mechanisms.

The *boost and bounce theory* (Olivers & Meeter, 2008) posits that an AB is the product of inhibitory feedback that suppresses the representation of potential distractors to protect T1 from interference, even if the “distractor” is the second target. The feedback is actively determined by an “input filter”, which promotes targets to working memory (i.e., targets are “boosted”) and suppresses distractors (i.e., distractors are “bounced”). For example, if the input filter detects that the identity of T1 matches the task goal of identifying letters, it will promote T1 to working memory to be processed and reported later. Since this “boost” has a slight delay, it can also enhance processing for a subsequent target, which results in lag-1 sparing. If, however, the item following T1 is a distractor, the input filter will “bounce” or suppress the following items, even if those items are targets, to protect the ongoing consolidation of T1 in working memory, which results in an AB.

In the *threaded cognition model* (Taatgen et al., 2009), a “central processor” creates “production rules” (i.e., cognitive control) that identifies targets and determines whether the targets or non-targets are consolidated or rejected to protect consolidation, respectfully. Precautionary production rules suppress target detection to protect ongoing consolidation of T1, which causes an AB if other targets appear during this timeframe. In other words, according to this model, an AB is the result of exerting of too much cognitive control in order to protect the representation of T1 from possible interference.

Both cognitive control models posit that the application of too much cognition control suppresses future item detection, which causes an AB to subsequent targets. If these models are correct, it would imply that people who are better at distributing or disengaging cognitive control should also have attenuated AB magnitude. Indeed, the individual differences literature have shown that some people, known as *nonblinkers*, display little to no AB, which is relatively stable over time (Dale, Dux, & Arnell, 2013; Willems & Martens, 2016) and is not the result of practice or training (Enns, Kealong, Tichon, & Visser, 2017). In addition, if the underlying cause of the AB is a domain-general mechanism (i.e., cognitive control), we may find that the AB is related to other attentional or cognitive process such as problem solving.

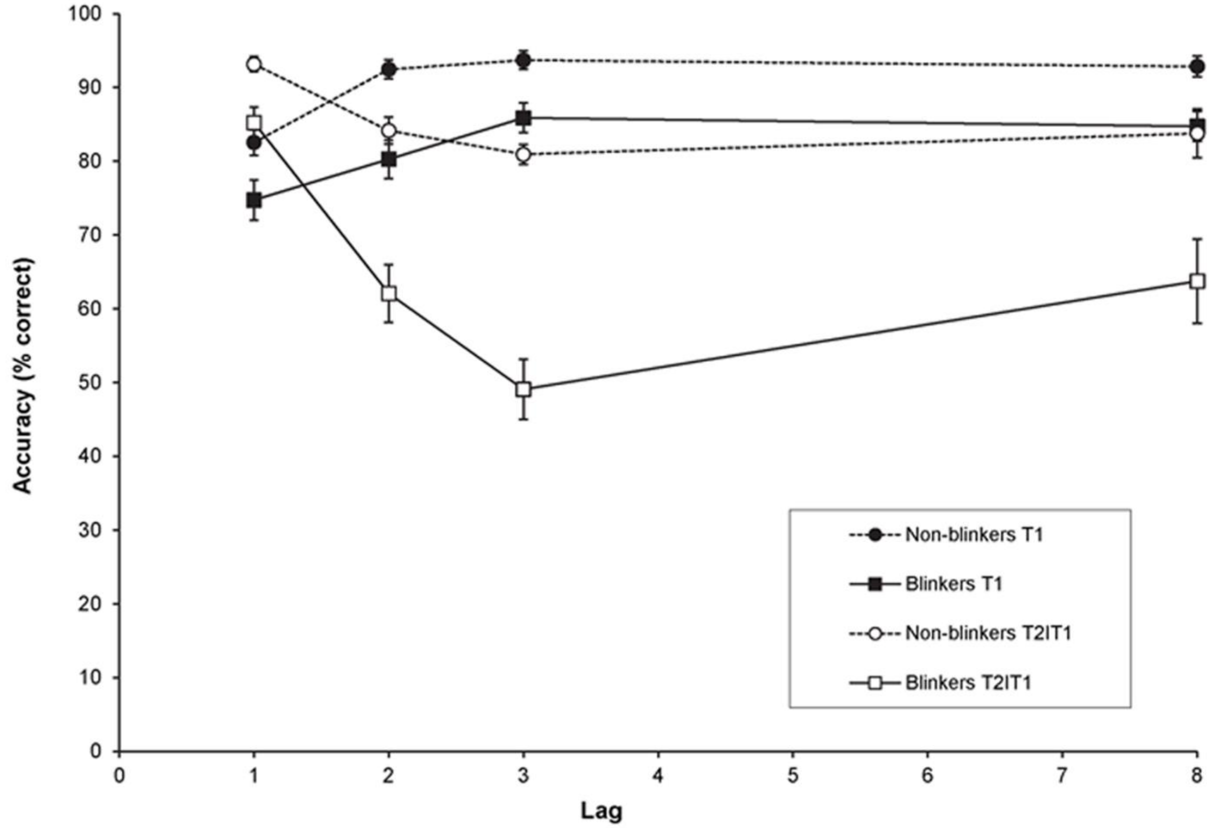


*Figure 13.* Performance of nonblinkers and blinkers on a standard RSVP task. Nonblinkers demonstrate attenuated attentional blinks (i.e., relatively high accuracies of target 2 identification) at lags 2 and 3 compared to blinkers (who demonstrate significant decrements in accuracy). Reprinted from "Individual Differences in the Attentional Blink: The Temporal Profile of Blinkers and Non-Blinkers" by Willems, C., Wierda, S. M., van Viegen, E., & Martens, S., 2013, *PLoS ONE*, *8*(6), p. 5. Copyright 2013 by Willems et al.

### 4.1.1 Individual Differences in Attentional Blink Magnitude

Some people perform almost equally accurately across all lags, thus showing little to no AB compared to the normally robust AB effect observed in standard RSVP tasks (e.g., Martens & Valchev, 2009; Slagter & Georgopoulou, 2013; Willems, Wierda, Viegen, & Martens, 2013; and see Figure 13, reprinted with permission from Willems et al., 2013). These people, known as *nonblinkers*, may show an attenuated AB because they are better at exerting an optimal amount of top-down attentional control and do not overinvest cognitive control when attending to the first target or distractors. For example, in the *threaded cognition model*, individuals who exhibit little to no AB may not apply the overprotective production rules (i.e., less top-down cognitive control); thus, they will be able to detect subsequent targets (i.e., T2) even when working memory is consolidating T1 (Taatgen et al., 2009).

According to the *overinvestment hypothesis*, reducing cognitive control may prevent T1 (or distractors) from receiving too much attention, which should free up attention for the detection of T2 (e.g., MacLean & Arnell, 2011). Indeed, people show reduced AB magnitudes when they perform the RSVP task with simple dual tasks such as listening to music or determining the presence of a red dot, which reduces the amount of cognitive control allocated toward the RSVP task (Olivers & Nieuwenhuis, 2006; Taatgen et al., 2009). Furthermore, dual tasks appear to attenuate AB magnitude by reducing attention to T1 or by reducing inhibition of subsequent distractors, as indexed by smaller P3 amplitudes when T2 was correctly identified (Wierda, Rijn, Taatgen, & Martens, 2010). This explanation is further corroborated by the finding that larger P3 amplitudes correlate with larger attentional blinks, suggesting that an overinvestment of attention to the first target or subsequent distractors may underlie the AB (Martens, Elmallah, London, & Johnson, 2006).

Reduced overinvestment of cognitive control or attention may also explain why open-monitoring (OM) but not focused attention (FA) meditation reduces AB magnitude (Colzato, Sellaro, Samara, Baas, & Hommel, 2015; Slagter et al., 2007; van Vugt & Slagter, 2014). People demonstrated attenuated AB magnitudes after receiving OM meditation training for three months (compared to baseline). This attenuation of AB was also greater for individuals trained in OM meditation than for novice meditators. These results suggest that recent intensive practice in OM meditation, in combination with meditation experience, was pivotal in inducing an attentional state conducive to performing an AB task. Moreover, when OM-meditators demonstrated smaller P3b (i.e., oddball) responses to T1, which reflects reduced attentional capture by T1, they also demonstrated greater accuracy in reporting T2 (Slagter et al., 2007). Expert meditators showed attenuated AB magnitudes when they performed a standard RSVP task while engaging in OM meditation compared to when they were engaged in FA meditation (van Vugt & Slagter, 2014). The attenuating effect of OM meditation on subsequent AB magnitudes also generalizes to novice meditators in some studies.  For example, a single session of OM meditation reduced AB magnitude compared to a single session of FA meditation, which increased AB magnitude compared to no meditation (Colzato et al., 2015). The findings from these studies suggest that OM meditation may promote a less selective attentional state and may prevent an overinvestment of cognitive control (particularly, preventing too much attention from being invested in the first target or distractors), resulting in reduced AB. Conversely, FA meditation may promote a more selective attentional state that engages more cognitive control and does not benefit performance on an RSVP task.

However, too little cognitive control also has a negative effect on AB magnitude; particularly, too little cognitive control results in reduced ability to suppress distractors, resulting in an AB. For example, older adults who are less able to inhibit irrelevant information also have more robust ABs than their younger counterparts (Georgiou-Karistianis et al., 2007; van Leeuwen, Müller, & Melloni, 2009). Some evidence suggests that that nonblinkers may have attenuated ABs because they are better able to ignore distracting stimuli (Dux & Marois, 2008; Martens & Valchev, 2009; Willems et al., 2013), or they invest less attention to distractors than blinkers as indexed by reduced distractor-related frontal neural activity during non-target trials (Martens, Munneke, Smid, & Johnson, 2006). Nonblinkers tend to demonstrate better executive control of working memory, which suggests that they may be better at allocating optimal amounts of attention during RSVP tasks (Arnell, Stokes, MacLean, & Gicante, 2010; Arnell & Stubitz, 2010).

Indeed, some research supports the idea that nonblinkers may be able to exert an optimal amount of cognitive or attentional control to avoid an attentional blink. For example, applying anodal tDCS over the left dorsolateral prefrontal cortex (left DLPFC), which should modulate the excitability of areas involved in selective attention and maintenance of working memory, did not change AB magnitude in general. However, when considering baseline AB performance, the application of anodal tDCS over left DLPFC had contrasting effects on subsequent AB magnitude: Blinkers showed reduced AB magnitude after tDCS, but non-blinkers showed increased AB magnitude after tDCS (London & Slagter, 2015). Thus, some optimal amount of attentional control may be necessary for good RSVP performance, and the amount of cognitive control that one needs to exert depends on how selective their attention is at baseline. A similar interplay between individual differences in attentional selectivity and the exertion of cognitive control exists in the creativity literature (for a review, see Zabelina, 2018). Specifically, creative people may need to exert more cognitive control to overcome their “leaky” attentional filters or their generally less selective attention.

Additionally, nonblinkers may have more flexible attentional control—the ability to engage and disengage cognitive control when required– rather than persistent attentional control that may underlie overinvestments of attention. For example, OM meditation is said to increase flexibility of attentional control (e.g., Lutz, Slagter, Dunne, & Davidson, 2008), which can also explain why OM meditation reduces AB magnitude (Colzato et al., 2015; Slagter et al., 2007; van Vugt & Slagter, 2014). Better attentional flexibility may have implications related to problem solving. Particularly, more persistent attentional control (i.e., better working memory) is beneficial to analytic problem solving (Wiley & Jarosz, 2012) whereas more flexible attentional control may benefit insight solving.

### 4.1.2 Individual Differences in Problem Solving and Attentional Blink Magnitude

If the attentional mechanisms underlying AB are domain-general, the depth of AB may be associated with other cognitive processes that depend on the same domain-general mechanisms. Prior studies have demonstrated domain-general relationships between problem solving and attentional selectivity in space; this study extends the current literature by investigating whether the relationship between selective attention and problem solving generalizes to attentional selectivity that occurs over time.

There are several indirect links between problem solving processes and the depth of (or magnitude of) attentional blink. Manipulations that reduce AB magnitude also tend to induce more insight solving in different experiments. For example, both insight solving and reduced AB magnitudes have been associated with more mind wandering, which is an index of reduced executive control. People who tend to mind wander show smaller attentional blinks (Thomson, Ralph, Besner, & Smilek, 2015), and less mind wandering (i.e., more mindfulness) is associated with less insight problem solving and more analytical problem solving (Zedelius & Schooler, 2015). Open monitoring (OM) meditation reduces AB magnitude (Colzato et al., 2015; van Vugt & Slagter, 2014), and it also improves insight solving (Colzato et al., 2017). Additionally, inducing people into a positive mood increases insight solving (Subramaniam et al., 2009) and decreases AB magnitude (Olivers & Nieuwenhuis, 2006; Vermeulen, 2010). Related to this, both attentional blink and insight solving have been related to higher dopaminergic activity as indexed by spontaneous eye blink rates. Reduced AB magnitude was associated with increased spontaneous eye blinks (Colzato, Slagter, Spapé, & Hommel, 2008). People also blink more frequently prior to insight solutions (Salvi, Bricolo, Franconeri, Kounios, & Beeman, 2015).

Given the indirect links between problem solving and AB, it is conceivable that individual differences in AB magnitude (i.e., nonblinkers vs blinkers) and problem solving processes (i.e., insight solvers vs analytic solvers) may share related attentional processes. Particularly, we were interested in whether nonblinkers and blinkers tend to solve problems with either insight or analysis. In the current study, we investigated this potential relationship by examining performance on a Compound Remote Associates task, which provided a measure of insight and analytic problem solving, with AB magnitude, which is the difference in the accuracy of T1 and T2 identification as a function of lag. In one session, participants attempted to solve a set of Compound Remote Associates (CRA) problems. For each CRA problem, participants were asked to come up with a fourth solution word that can form a common compound word or phrase with each of the three problem words. In another session, participants performed a Rapid Serial Visual Presentation (RSVP) task, which provided a measure of AB magnitude. In each trial of the RSVP task, participants viewed a series of rapidly presented 18 alphanumeric symbols and were asked to identify two letters (T1 and T2) that appeared within the series. The number of CRA problems solved with insight and analysis was then correlated with AB magnitude.

Given the exploratory nature of this investigation, we had two contrasting hypotheses regarding the relationship between AB magnitude and insight and analytic problem solving. Insight problem solving may require less selective attention (e.g., Ansburg & Hill, 2003; Wegbreit et al., 2012; see Chapter 2), and people with reduced inhibitory control (i.e., reduced ability to filter or ignore irrelevant information) are better at solving insight problems when irrelevant information becomes relevant (e.g., Kim et al., 2007; May, 1999). If insight benefits from reduced attentional control and AB is a result of poor attentional control, then we might expect that people who demonstrate larger AB magnitudes (i.e., blinkers) also tend to solve problems with insight. If reduced AB magnitudes is related to a better ability to selectively attend in time, then we would expect that nonblinkers also tend to be analytic solvers.

However, given the numerous indirect links between the depth of AB and insight solving, it seems more plausible that people with little to no AB (i.e., nonblinkers), relative to people who demonstrate a normal to large AB (i.e., blinkers), would tend to solve problems with insight. For example, positive affect could facilitate insight and reduce AB via the same attentional mechanisms, perhaps by relaxing executive control to become more flexible or less perseverant (e.g., Dreisbach & Goschke, 2004). Similarly, a state of distributed attention during mind wandering and open monitoring meditation that may be conducive to both AB magnitudes and facilitate insight solving. Thus, it is more conceivable that people who do not overinvest attention (i.e., smaller AB magnitudes) may tend to be insight solvers, whereas people who overinvest attention in the first target or subsequent distractors may tend to be analytic solvers.

## 4.2 Study 4 Methods

**Participants.** 86 people (48 females, mean age = 18.80) participated in this study for partial course credit. Data from one participant was excluded due to missing CRA data (i.e., only data from the third block of CRAs were recorded). Data from six participants were excluded from the final analyses due to being outliers on T1 accuracy. Data from five participants were excluded from analyses due to being outliers on CRA solving performance (see Section 3.5 for more information on the outlier analyses). The final analyses consisted of data from 74 participants (40 females, mean age = 18.81). All participants were native English speakers and consented to participate in the study, which was approved by the Northwestern University Institutional Review Board.

**Materials and procedure overview.** This study examines the relationship between individual trait differences in attentional blink magnitude and problem solving processes (i.e., insight versus analytic problem solvers). To prevent carryover or transfer effects, participants performed the Rapid Serial Visual Presentation (RSVP) task in one study session, and they attempted the Compound Remote Associates (CRA) problems in a separate study session. That is, participants always completed the RSVP and CRA tasks on different days, ranging from one day to a week apart. Whether the participants received the RSVP or CRA task in the first session was counterbalanced across participants. Each study session was approximately 30 minutes long, totaling 1 hour across two study sessions. Participants were seated 59 cm from the screen for the entire experiment, and all tasks were programmed in PsychoPy (Peirce, 2007).

**Rapid serial visual presentation (RSVP) task.** In the RSVP task (Figure 6), 18 alphanumeric symbols consisting of 16 random digits and 2 random letters were presented rapidly and serially in the center of the display on a white background. Each symbol was presented for 76 ms without an interstimulus interval; in total, each trial (i.e., one presentation of one RSVP stream of 18 items) was presented for approximately 1.5 seconds.

Participants were asked to identify two targets (i.e., letters) embedded within a stream of 16 distractors (i.e., digits). The targets included any letter from Standard English, except “I”, “O”, “Q”, “V”, and “Y”, and they were randomly selected in each trial with the constraint that the two targets were different letters. The distractors included any number from 0 to 9, and they were randomly selected in each trial with the constraint that the selected digit was not shown twice in succession. The alphanumeric symbols subtended visual angles ranging from .46° vertically x .14° horizontally to .46° vertically x .46° horizontally.

As in other studies investigating individual differences in AB magnitude, the first target (T1) was always presented in the fifth position in the RSVP stream (e.g., Slagter & Georgopoulou, 2013; Willems et al., 2013; see Figure 14). For any given trial, the second target (T2) randomly appeared at either lag 1, 2, 3, or 8; thus, T2 appeared at position 6, 7, 8, or 13 (out of 18 possible positions), respectively, in the RSVP stream. The stimulus onset interval (SOA) between T1 and T2 was either 76 ms (lag 1), 152 ms (lag 2), 228 ms (lag 3), and 608 ms (lag 8).

At end of each trial (i.e., one stream of 18 alphanumeric symbols), participants were asked to identify the target letters via keyboard input. Participants were encouraged to input the target letters in the order they appeared, but responses were accepted in either order.

Participants performed a practice block of eight trials. Then, participants performed two experimental blocks of 72 trials each (i.e., 72 streams of 18 items). The targets appeared at each lag (i.e., lags 1, 2, 3, and 8) 18 times per block, for a total of 36 times in the experiment. Participants were given short breaks between each block. The RSVP task was self-paced in that participants could begin each trial when they were ready. Participants did not receive feedback during the practice and the experimental blocks.

**Compound Remote Associates (CRA) task.** As in Studies 1 and 2 (see Figure 2), participants were asked to come up with a solution word (e.g., APPLE) that can form a common compound word or phrase with each of the three problem words (e.g., PINE—CRAB—SAUCE), which appeared on three separate rows in the center of the screen on a white background. The size of the problem words and font were the same as in Studies 1 and 2. Participants did not receive feedback during the practice and the experimental blocks.

First, participants attempted three practice problems. Some participants attempted three additional practice problems if they were unable to solve any of the first three practice problems. Participants attempted 72 CRA problems in three blocks (i.e., 24 CRA problems per block) with a short break between blocks. The CRA task was self-paced in that participants could begin each trial when they were ready. Participants had 15 seconds to solve each problem. If they did not solve the problem within the time limit, the experiment automatically advanced to the ready screen preceding the next trial. When participants solved a problem, they were prompted to verbalize the solution to the experimenter. Then, they were asked whether they solved the problem with insight or analysis. Finally, they were automatically advanced to the ready screen preceding the next trial.

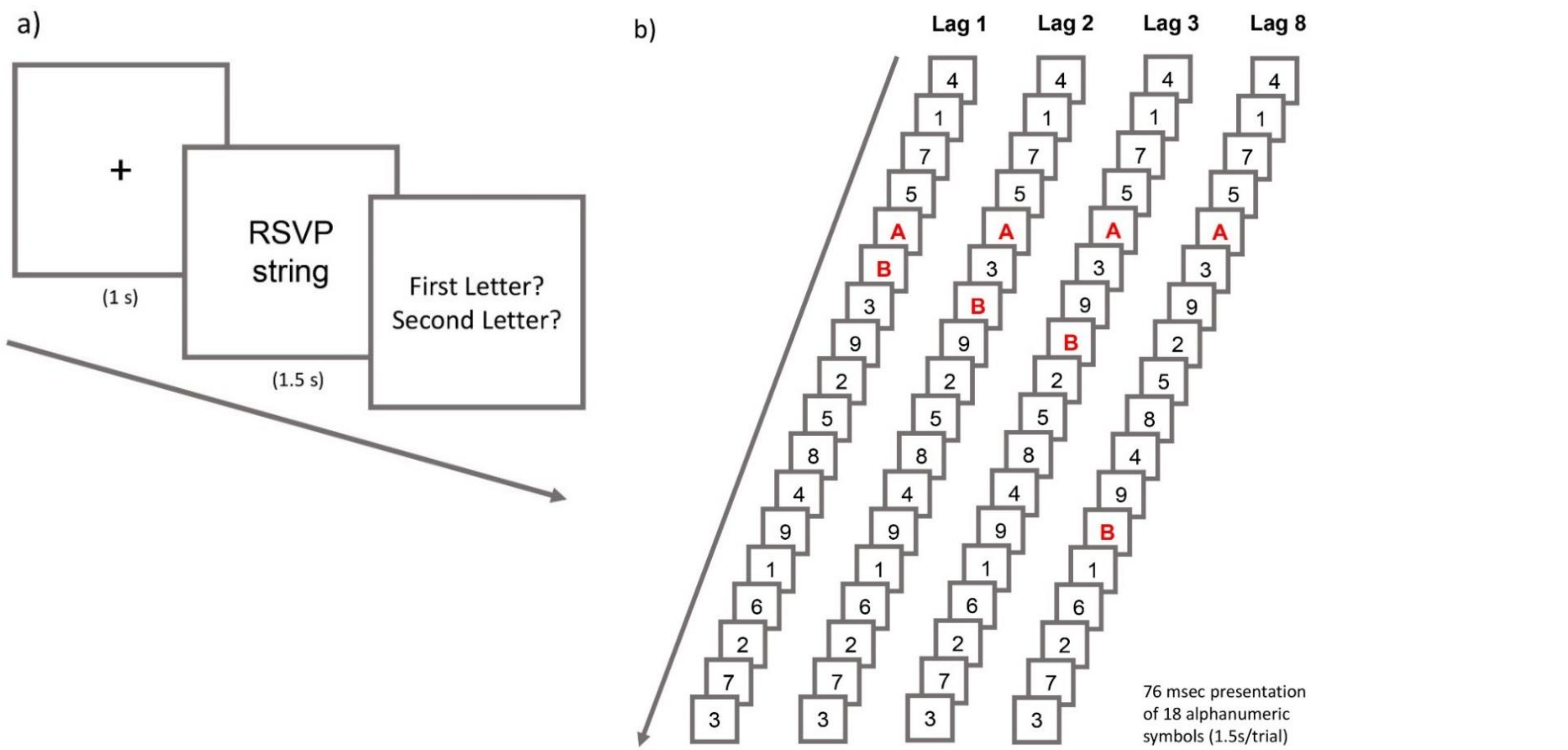


*Figure 14.* Schemata of the Rapid Serial Visual Presentation (RSVP) paradigm. a) An example trial of the RSVP task is depicted. Participants were shown a rapidly presented stream of 18 alphanumerical symbols and were asked to identify two alphabetical targets (T1 and T2 corresponding to the first and second alphabetical targets, respectively). b) An example of RSVP streams. The first target (T1) always appeared in the fifth position within the RSVP stream. The second alphabetical target (T2) appeared at lag 1 (i.e., in the 6th position), lag 2 (i.e., in the 7th position), lag 3 (i.e., in the 8th position), and lag 8 (i.e., in the 13th position).

**4.3 Study 4 Results**

**Data analyses.** Following other studies investigating *non-blinkers* (e.g., Willems et al., 2013), AB magnitude was computed using this formula:

$$\text{AB magnitude} = \left( \frac{\overline{T1} - T2|T1_{lag2}}{\overline{T1}} + \frac{\overline{T1} - T2|T1_{lag3}}{\overline{T1}} \right) \div 2 \times 100$$

In this formula, $\overline{T1}$ represents the mean accuracy of T1 across all trials. $T2|T1_{lag}$ represents the accuracy of T2 at a given lag (i.e., lags 2 or 3) when T1 was reported correctly.

Shapiro–Wilk tests indicated that AB magnitude in our sample was normally distributed as was the number of correct CRA solutions, the number of correct insight solutions, and the number of correct analytic solutions.

To determine potential outliers on RSVP task and CRA performance, we created box plots of T1 performance (i.e., accuracy in identifying the first target) and CRA solving performance (i.e., the percent of correctly solved CRA problems out of the total number of solving attempts). Mean T1 accuracy was 94.89% (*SD* = 4.96%), prior to outlier detection. Mean CRA solving performance was 89.01% (*SD* = 12.87%) prior to outlier detection. The box plot for T1 performance showed that six data points (T1 performance under 86.81%) were considered extreme outliers (Figure 15a). The box plot for CRA solving performance showed that five data points (CRA solving performance under 66.67%) were considered extreme outliers (Figure 15b). Mean T1 accuracy was 95.93% (*SD* = 3.01%) after removing the six outliers from the analysis, and mean CRA solving performance was 91.96% (*SD* = 7.57%) after removing the five outliers from the analysis.

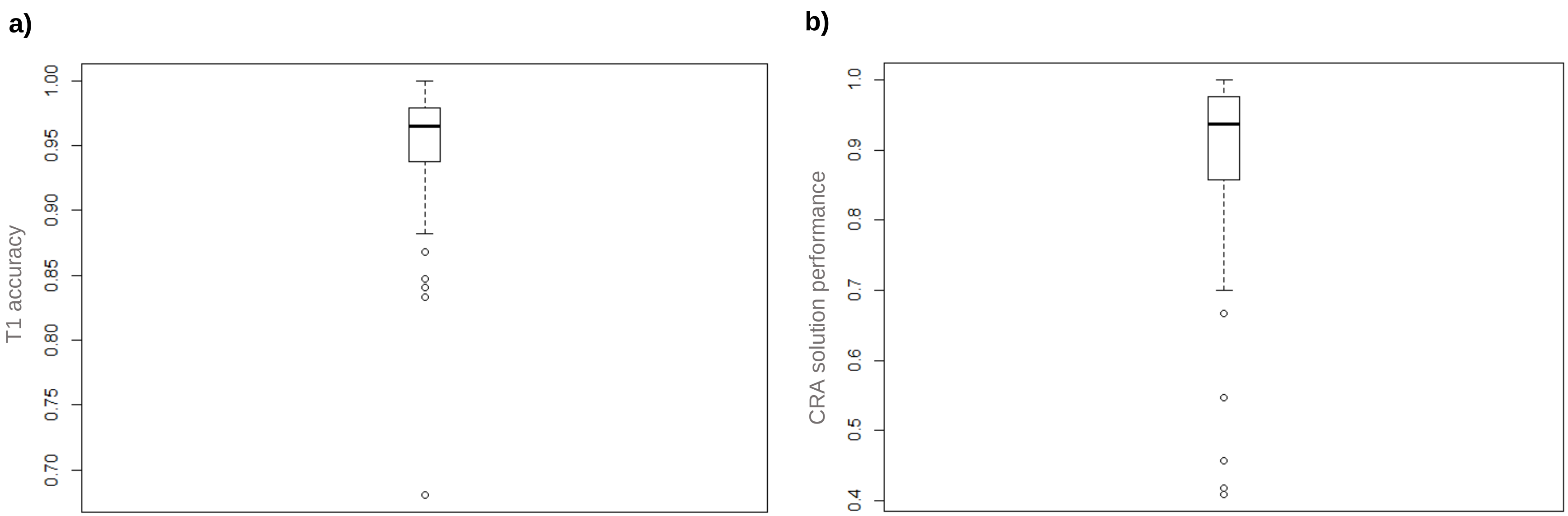


*Figure 15*. Box plots of T1 accuracy and CRA solving performance in Study 4. a) This box plot shows the 6 outliers for T1 performance (i.e., accuracy in identifying the first target in the RSVP stream was under 86.81%). Two participants had the same T1 accuracy and are represented by a single data point. b) This box plot shows the 5 outliers for CRA solving performance (i.e., the proportion of correctly solved problems compared to the number of total solving attempts made was under 66.67%).

Since the data are normally distributed, further analyses used parametric tests. All analyses in this study, including the normality and outlier tests described here, were performed in R.

**RSVP task performance**. The general trajectory of T2|T1 (i.e., accuracy of identifying T2 when T1 was correct) performance from our RSVP task replicate the trajectory of AB found in other studies (Figure 16a). That is, the plot shows lag-1 sparing, robust ABs at lags 2 and 3, and a recovery from AB at lag 8. AB magnitudes ranged from -0.70% to 65.60%, and the mean AB magnitude was 27.55% (*SD* = 16.32%). T2|T1 accuracies at lag 2 and 3, where AB would typically be maximally present, were 72.17% (*SD* = 15.81%) and 67.05% (*SD* =18.76%), respectively.

Additionally, when dividing the sample into quartiles, nonblinkers (i.e., participants in the lowest quartile of AB magnitudes; *n* = 19; *M* = 7.19%, *SD* = 4.49%) demonstrated shallower ABs compared to blinkers (i.e., participants in the highest quartile of AB magnitudes; *n* = 18; *M* = 49.82%, *SD* = 6.88%; Figure 16b). That is, T2|T1 accuracies were overall higher for nonblinkers at lag 2 (*M* = 90.13%, *SD* = 6.64%) and lag 3 (*M* = 89.34%, *SD* = 4.95%) than for blinkers at lag 2 (*M* = 50.62%, *SD* = 9.33%) and lag 3 (*M* = 45.10%, *SD* = 11.73%). For nonblinkers, AB magnitudes ranged from -0.70% to 14.35%, and T2|T1 accuracies ranged at lag 3 (i.e., where AB was maximally present in this sample) from 80.56% to 100%, showing that nonblinkers exhibited little to no AB. For blinkers, AB magnitudes ranged from 41.01% to 65.60%, and T2|T1 accuracies at lag 3 ranged from 25.71% to 69.44%, showing that blinkers exhibited a robust AB.

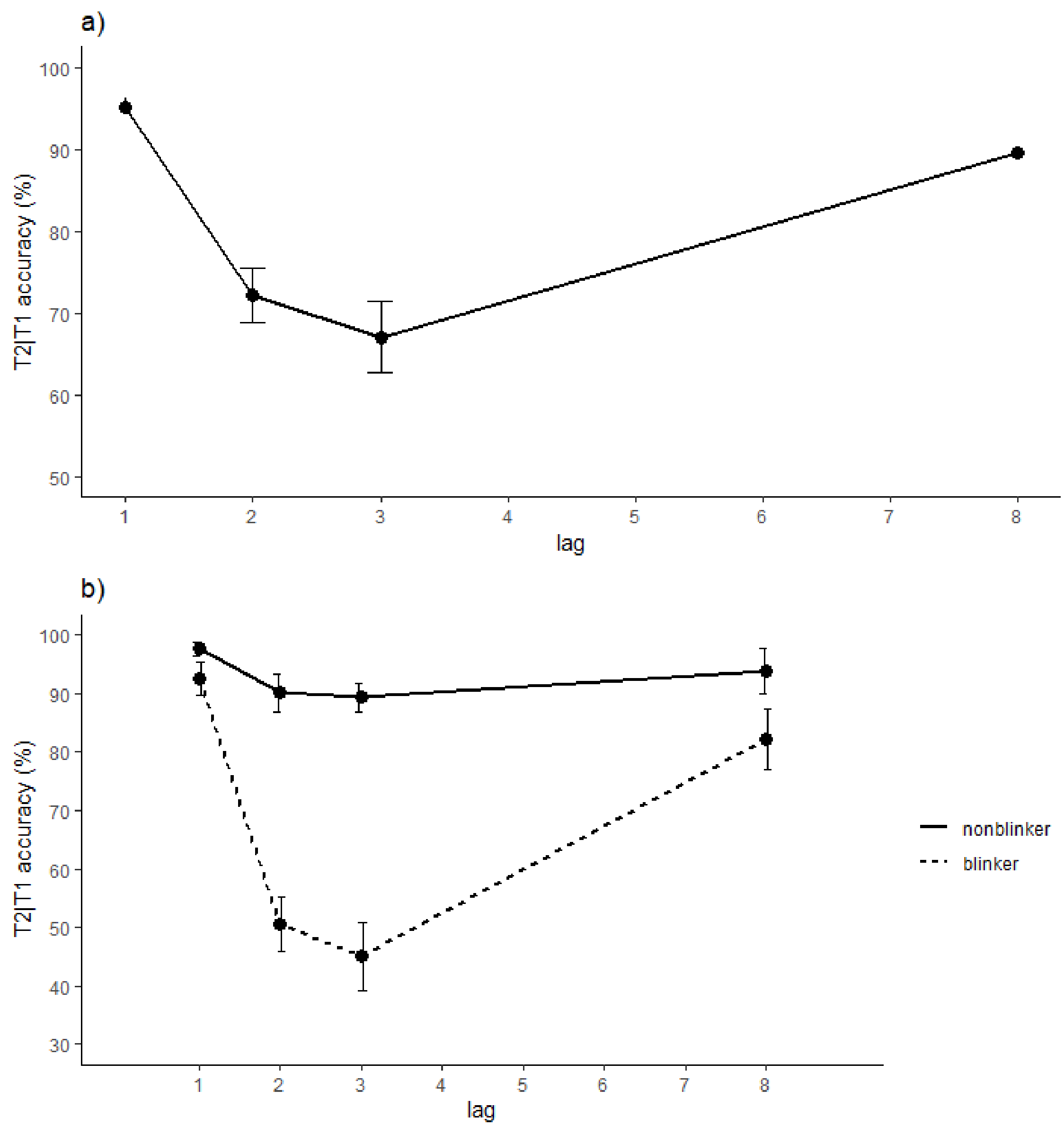


*Figure 16. Trajectory of T2|T1 performance of blinkers and nonblinkers in Study 4.* a) This graph demonstrates the overall trajectory of T2|T1 (i.e., the accuracy of identifying T2 when T1 was correct). Error bars represent standard error of the mean. b) This graph demonstrates the performance of nonblinkers (solid line) compared to blinkers (dashed line). Error bars represent standard error of the mean.

**CRA performance.** On average, participants solved 31.81 (*SD* = 8.06) or 44.2% of the CRA problems. As in our previous studies, we excluded solutions that participants solved within 2 seconds because these "fast recognitions" have different phenomenological and neural underpinnings from insight solutions (Cranford & Moss, 2011; Cranford & Moss, 2012); these fast recognitions constituted 3.48% of the correct solutions. Participants were more likely to solve with insight, which constituted 58.84% of the correct solutions, ($M = 18.72$, $SD = 7.77$) than with analysis ($M = 11.97$, $SD = 6.78$), $t(73) = 4.56$, $p < .01$, which constituted 37.64% of the correct solutions. [When we included outliers in the analyses, participants solved 43.18% of the CRA problems, 60.08% with insight, 36.73% with analysis, and 3.14% by fast recognition.] The order in which participants received either the RSVP or CRA task first did not affect the total number of correct, insight, or analytic solutions reported (all *p*'s > .05).

**Individual differences between AB magnitude and problem solving.** To assess the relationship between the depth of AB and problem solving processes, we ran Pearson correlation tests between AB magnitude and total correct, insight, and analytic solutions (Figure 17). The correlation between AB magnitude and the number of correctly solved CRA problems was not reliable (Figure 17a). We predicted that smaller AB magnitudes (i.e., nonblinkers) should be related to more insight solutions and larger AB magnitudes (i.e., blinkers) should be related to more analytic solutions. The correlation between AB magnitude and number of insight solutions weakly trended in the negative direction ($r = -.13$), but it was not reliable ($p > .05$; Figure 17b). Finally, the correlation between AB magnitude and number of analytic solutions weakly trended in the positive direction ($r = .12$), but it was also not reliable ($p > .05$, Figure 17c).

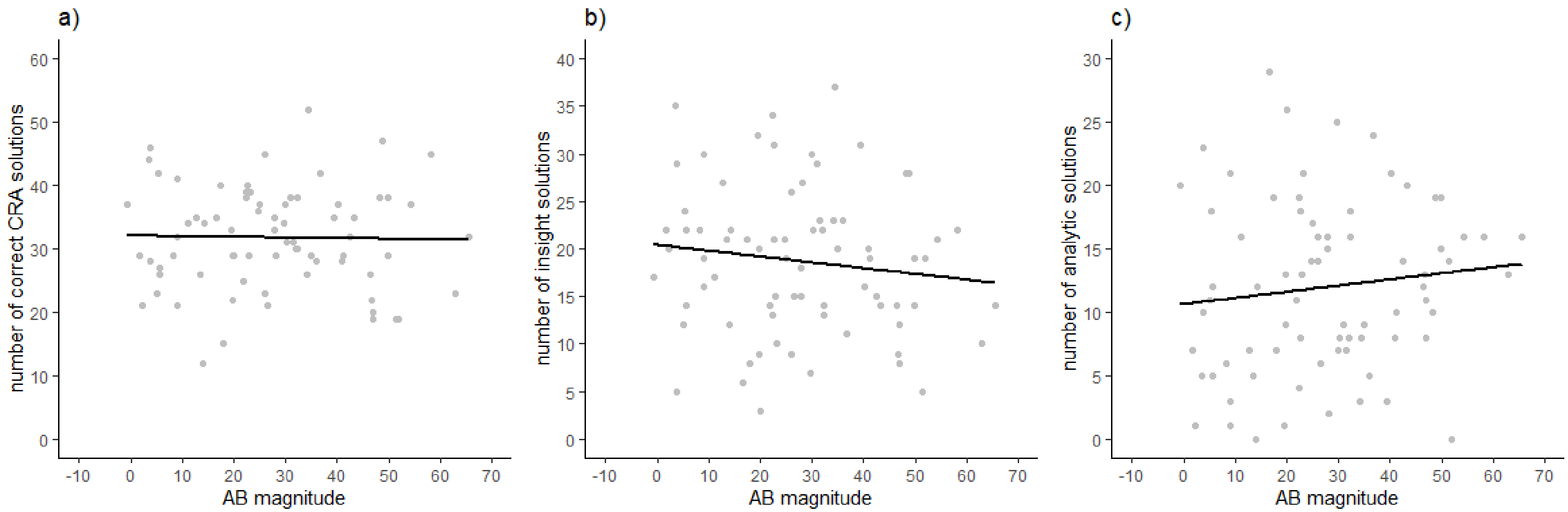


*Figure 17. Correlations between attentional blink (AB) magnitude and total correct, insight, and analytic CRA solutions.* a) This scatterplot demonstrates the correlation between AB magnitude the total number of correct solutions. Pearson's *r* was close to 0, signifying that there is no relationship between AB magnitude and general CRA solving ability. b) This scatterplot demonstrates the slightly negative correlation between AB magnitude the total number of insight solutions. Pearson's *r* was -.13, signifying a weak but not reliable negative relationship between AB magnitude and tendency to solve problems with insight. c) This scatterplot demonstrates the slightly positive correlation between AB magnitude the total number of analytic solutions. Pearson's *r* was .12, signifying a weak but not reliable positive relationship between AB magnitude and tendency to solve problems with analysis.

In addition to the correlations, we also looked at the relationship between nonblinkers, blinkers, and problem solving processes by comparing insight, analysis, and total solving for participants in the lowest quartile of AB magnitudes (i.e., nonblinkers, $n = 19$) to participants in the highest quartile of AB magnitudes (i.e., "deep" blinkers; $n = 18$). We predicted that nonblinkers should solve more problems with insight than with analysis whereas blinkers should solve more problems with analysis than with insight. In addition, we predicted that nonblinkers would solve more problems with insight than blinkers, blinkers would solve more problems with analysis than nonblinkers. A 2 (blinker type: *nonblinker* vs *blinker*) x 2 (problem solving process: *insight* vs *analysis*) showed a reliable interaction between blinker type and problem solving process (Figure 18), $F(1, 33) = 6.27$, $p = .01$, $\eta^2 = .06$, and a reliable main effect of problem solving type, $F(1, 33) = 21.92$, $p < .01$. Post-hoc Tukey's HSD tests revealed that blinkers had reliably more insight solutions than nonblinkers had analytic solutions ($p = .02$), nonblinkers had reliably more insight solutions than blinkers had analytic solutions ($p < .01$). As we predicted, nonblinkers had reliably more insight solutions than they had analytic solutions ($p < .01$). Planned comparisons (independent samples t-tests) revealed that nonblinkers ($M = 30.89$, $SD = 8.80$) did not solve more CRA problems than deep blinkers ($M = 29.89$, $SD = 8.82$), $t(35) = .35$, $p > .05$. Consistent with our prediction, nonblinkers solved more CRA problems with insight ($M = 20.32$, $SD = 7.11$) compared to deep blinkers ($M = 16.17$, $SD = 6.39$), but this result was only marginally reliable, $t(35) = 1.86$, $p = .07$, $d = .61$. Conversely, deep blinkers solved marginally more CRA problems with analysis ($M = 13.00$, $SD =4.83$), $t(35) = -1.67$, $p = .10$, $d = .55$, than nonblinkers ($M = 9.63$, $SD = 7.14$).

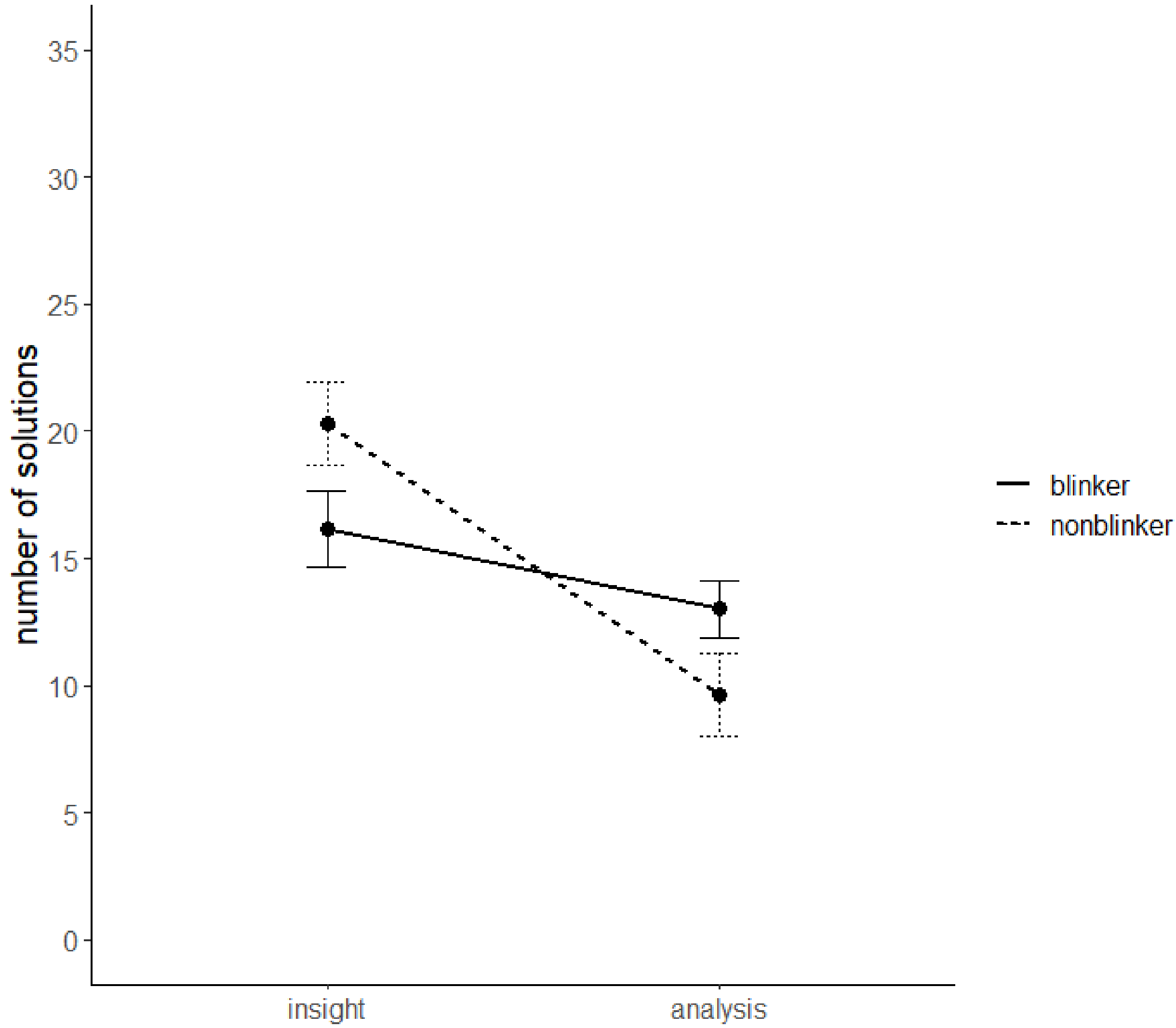


*Figure 18.* Interaction between blinker type (nonblinker vs blinker) and problem solving processes (insight vs analysis).

**4.4 Study 4 Discussion**

This study sought to investigate whether the attentional processes underlying attentional blink (AB) are domain-general and, if so, whether those same attentional processes also underlie insight and analytic problem solving. Given that people who are better at distributing their attention across time also demonstrate smaller AB magnitudes (i.e., nonblinkers), we expected that nonblinkers should also tend to demonstrate more insight solving, which should require less selective or more distributed attention. Conversely, people who overinvest attentional control, leading to more selective attention on the first target or irrelevant distractors, also demonstrate larger AB magnitudes (i.e., "blinkers"). Thus, we expected that blinkers should demonstrate more analytic problem solving, which is related to more selective attention.

We did not find reliable correlations between AB magnitudes and insight and analytic problem solving; however, they did tend to weakly trend in the predicted directions and in opposite directions. That is, people with smaller AB magnitudes tended to solve more CRA problems with insight and fewer problems with analysis, whereas people with larger AB magnitudes tended to solve more CRA problems with analysis and fewer problems with insight. It is possible that these correlations would be more robust with a larger sample of nonblinkers; only 19 of 74 participants in our sample fell within the range of AB magnitudes for nonblinkers found in other individual differences studies (e.g., Willems et al., 2013). However, it is equally plausible that some attentional or executive control mechanisms that underlie the AB do not completely overlap with insight or analytic problem solving.

We also investigated individual differences in problem solving performances of nonblinkers and "deep" blinkers (i.e., people who demonstrated deep ABs) by comparing participants in the top and bottom quartiles of AB magnitude. We found a reliable interaction between problem solving process (i.e., the number of CRA problems solved with insight and analysis) and blinker type (i.e., whether the participant was a nonblinker or blinker). Specifically, nonblinkers reliably solved more problems with insight than they did with analysis. Blinkers, however, did not demonstrate this relationship, and they did not solve more CRA problems with analysis than insight. Nonblinkers also solved more CRA problems with insight than deep blinkers, though this finding was only marginally reliable. In addition, deep blinkers solved more CRA problems with analysis than nonblinkers, though, again, this difference was not quite reliable.

The findings in this study suggest that some components of attention or executive control may be shared between the ability to avoid an AB and insight problem solving and the inability to avoid an AB and analytic problem solving. However, the small and unreliable correlations between the depth of AB and problem solving may suggest that the underlying attentional mechanisms are not as domain-general as we expected, or there are other mechanisms that are unique to either AB or problem solving processes. For example, it is possible that the ability to distribute attention efficiently among targets is common between the ability to avoid an AB and insight solving (and conversely, the inability to distribute attention efficiently is common between an AB and analytic solving). At the same time, it is also possible that other factors that are important for insight solving such as verbal working memory, semantic activation, or the ability to converge on a correct semantic association were unbalanced in our small sample of nonblinkers and blinkers. This could, in turn, obfuscate any reliable contributions from shared attentional mechanisms. Given the small sample size (i.e., 19 nonblinkers, 18 deep blinkers) but relatively moderate effect sizes, we might expect that a replication of this study with a larger sample of nonblinkers and controlling for differences in verbal working memory and verbal intelligence may produce more reliable results.

Previous studies showed numerous indirect links between manipulations that reduce AB magnitude and induce insight solving (e.g., positive mood, open monitoring meditation). If the depth of AB and problem solving processes share common attentional mechanisms, the manipulations that reduced AB magnitude may also modulate subsequent insight and vice versa. For example, instructing people to “concentrate less” reduced AB (Olivers & Nieuwenhuis, 2006), and it may also be beneficial for insight solving, particularly when the solver has reached a mental impasse or are stuck on a dominant but incorrect solution. Additionally, understanding what component(s) of attention or executive control (if any) these manipulations modulate may bring us closer to understanding the attentional mechanisms required for insight solving. Another possibility for future study is the use of an RSVP task that also requires a semantic or conceptual component; perhaps an RSVP task that is parallel to the rapid object identification task used in the Wegbreit et al. (2012) study may be more conducive to insight solving, as it may require attention to weakly activated internal representations. Including a semantic component could more directly modulate conceptual attention, thus being more likely to influence problem solving.

In summary, this study suggests the possibility of an attentional link between the ability or inability to suppress or avoid an attentional blink and insight and analytic problem solving. That is, people who are better at avoiding an AB tend to solve problems with insight whereas people who are worse at avoiding an AB tend to solve problems with analysis. However, more research must be conducted to understand the extent of these relationships.

# Chapter 5: General Discussion

The purpose of this research was to investigate how the degree to which attention may be *more* or *less* selective affects future problem solving. That is, does performing a task that encourages one to focus on a smaller number of objects with greater resolution produce an attentional state that is conducive to analytic, but not insight, problem solving? Conversely, does performing a task that encourages one to diffusely distribute attention across numerous items at the cost of lower resolution produce a different attentional state that is conducive to insight, but not analytic, problem solving? Here, we investigated these questions in four studies wherein we manipulated the selectivity of attention in visual space to observe its effects on subsequent problem solving (Studies 1-3), and we examined the relationships between the ability to selectively attend across time and in individual problem solving tendencies (Study 4).

In our first two experiments (Study 1a), we manipulated the selectivity of attention using a modified version of the Navon letter task (Navon, 1977), and we measured subsequent changes in insight and analytic solving with Compound Remote Associates problems. Although the Navon letter task is typically used to index global and local attentional biases, we found (and replicated in Study 1b) that congruency effects (i.e., the difference in latencies when the global and local letters are incompatible than when they are compatible) were higher when people judged the identities of global letters (ignoring local letters) than when people judged the identities of local letters (ignoring global letters). As in other attention tasks that require inhibition (e.g., Stroop task), higher congruency effects indicate that the task demanded more selective attention and executive control. In both experiments, people who performed the letter task that produced the largest congruency effects (i.e., judged the identities of the global letters) subsequently solved more verbal problems with analysis, but not with insight, compared to baseline.

In Study 2, we replicated the effect of selective attention on subsequent analytic solving, again using a version of the letter task from Study 1. We were particularly interested in how the facilitatory effect on analytic solving changes when we vary the amount of interference from the local level (i.e., small letters) within the same global task. People who judged global letters that had more interference from the local letters (i.e., local-salient global letters) demonstrated large congruency effects and subsequently solved more problems with analysis compared to baseline. However, people did not reliably solve more problems with analysis (compared to baseline) after they judged global letters that had little interference from the local level, which produced smaller congruency effects than the local-salient version of the task. Taken together, the findings from Study 1 and 2 support the idea that performing a selective attention task can induce a selective attentional state (which could, in turn, also make conceptual attention more selective) that is conducive to subsequent analytic solving.

We were also interested in how individual differences in the ability to selectively attend to information were related to the tendency to solve problems with either insight or analysis, which we explored in Study 1c. People with larger congruency effects tended to solve more problems with insight at baseline (i.e., prior to any attentional modulation) whereas people with smaller congruency effects tended to solve more problems with analytic at baseline. Here, congruency effects on the letter task might also elucidate general differences in selective attention at baseline. People with generally less selective attention may have needed to engage in more selective attention to perform the letter task accurately at the cost of larger congruency effects. Conversely, people with generally more selective attention did not have to exert more selective attention to perform the letter task, which is reflected in smaller congruency effects. We did not, however, have other attentional measures or indices of working memory capacity or inhibitory control at baseline to confirm that people who demonstrated larger congruency effects also had generally less selective attention. Thus, future research should consider using other measures of selective attention or executive control of attention to determine baseline (i.e., without prior attentional manipulations) individual differences in selective attention. These measures could also be used to determine how performing the global letter task affects subsequent attention (i.e., whether attention becomes more selective).

While we did not use neuroimaging techniques in this study, we can speculate on the cognitive and neural mechanisms through which selective attention (as well as attention to the global level of information) may improve analytic, but not insight, solving. Previous studies have shown that attention to the global level of information (while ignoring the local level of information) evokes increased activity in the areas involved in conflict monitoring such as the dorsal anterior cingulate cortex (dACC; Weissman et al., 2003). Moreover, similar attention tasks appear to directly modulate neuronal activity in the ACC (Davis, Hutchison, Lozano, Tasker, & Dostrovsky, 2000). A result of detecting conflicting information is increased cognitive control through increased activity in the prefrontal cortex (PFC; Kerns, 2004), which enables accurate performance on this task by increasing selective attention. That is, the PFC is involved in sensory gating, or the process of filtering irrelevant distractors from sensory input (Chao & Knight, 1995), and it contributes to working memory processes that are involved in attentional control (Kane & Engle, 2003).

There is a dearth of neuroimaging literature on analytic problem solving; many studies on creative problem solving do not make the distinction between insight or creative solutions and analytic solutions, or they consider all solutions to so-called traditional "insight" problems to be insight. Future studies should try to find stronger evidence of discrete neural patterns, areas, and functional connectivity (or neural "hubs") that distinguish analytic solutions from insights. For the purpose of this discussion, however, we can speculate that analytic solving may share some of the same neural correlates as mathematical problem solving, which is often stepwise and requires retrieval from long-term memory (Liang, Jia, Taatgen, Zhong, & Li, 2014). Successful mathematical problem solving is related to higher working memory capacity and a greater ability to ignore irrelevant and distracting information and reinterpret problem representations (for a review, see Wiley & Jarosz, 2012). Algebraic problem solving was related to increased activity around the fontal gyri and dorsal lateral PFC (i.e., areas involved in working memory and executive control) and right precuneus (i.e., involved in selective attention) (Lee et al., 2007; Liang et al., 2014). Finally, increasing cognitive demands during algebraic problem solving also increases neural activity in the ACC and caudate nucleus, which reflects subsequent increases in cognitive control and attention.

Comparing the links between the correlates of attention and problem solving unfolds a story about the potential mechanisms through which a visual attention task that requires selective attention may influence subsequent problem solving. It is possible that the modulation of conflict monitoring and executive control (via the ACC and PFC) improves inhibition of *any* distracting information, including dominant or incorrect solutions for CRA problems, for a short duration following the attentional manipulation. Although we were not able to measure how long the effects last of the attentional manipulation last, it is not out of the possibility that the manipulation induced phasic attentional changes. For example, training cognitive control through tasks similar to the Simon Task can improve subsequent performance on specific cognitive control or attention tasks (Zinke, Einert, Pfennig, & Kliegel, 2012). Taken together, we speculate that performing an attention task engages cognitive control and subsequently increases selective attention that is conducive to analytic problem solving, which may rely on the ability to keep irrelevant information out of working memory. This story also supports dual process theories of creativity, in which creative problems can also be solved through a persistent, deliberate, and incremental search process (De Dreu, Baas, & Nijstad, 2008; (De Dreu, Nijstad, Baas, Wolsink, & Roskes, 2012).

We showed that people increase analytic, but not insight, solving after performing a visual attention task that increases selective attention. To answer our second question regarding the type of attention involved in insight solving, we used an ensemble statistics task to induce *less* selective attention and measured subsequent changes in problem solving (Study 3). Here, we found that people who performed an ensemble statistics task that required distributed attention subsequently solved more verbal problems with insight. This finding corroborates other literature that found less selective or more distributed attention is related to insight problem solving (Ansburg & Hill, 2003; Wegbreit et al., 2012). In contrast to analytic solving, it appears that the ability to distribute attention across several elements (visually and conceptually) is linked to insight solving. Unfortunately, there is a relative lack of neuroimaging research on the attentional mechanisms underlying ensemble statistics and related attentional constructs such as gist perception. Research on the relationship between cognitive control, distributed attention, and ensemble statistics is also scant. We hypothesize that distributed attention may increase insight solving by increasing the likelihood that distant semantic representations (that lead to the correct solution) are selected. It is possible that the neural mechanisms through which distributed attention leads to insight solving are similar to other manipulations that increased insight such as positive mood or open monitoring meditation. Thus, we might expect that the ensemble statistics task might engender activity from similar neural areas like the anterior cingulate cortex.

We did not, however, find that the version of the ensemble statistics task that was supposed to induce more selective attention increased subsequent analytic solving. We did not have another task to measure selective attention, however, we speculated that asking people to attend to a target circle fixated in the center of the display may have not demanded enough selective attention to be conducive to analysis. As we have previously discussed, future version of this task, which serves as a contrast to the averaged circles version that induced insight solving, should be more difficult in order to evoke more selective attention.

The first three studies investigated the influence of selective attention within a spatial domain. In Study 4, we shifted our focus to the temporal domain by investigating how the allocation of attention leading to (or avoiding) attentional blinks (AB) is related to insight and analytic problem solving. Although most of our findings from this study were not reliable, we saw a general trend in nonblinkers—people who can avoid an AB by allotting less attention to irrelevant distractors—solving more problems with insight and blinkers—people who overinvest attention on irrelevant information, leading to a robust AB—solving more problems with analysis. This pattern of results suggests that the ability to distribute attention across time is, much like the ability to distribute attention in space, more conducive to insight solving whereas selective attention (which has a negative effect in the Rapid Serial Visual Presentation task) is again more conducive to analytic solving. These findings also suggest that the attentional mechanisms common between problem solving and the AB are domain-general. For example, stimulating the left dorsolateral PFC, an area involved in executive functions including the maintenance of working memory, with tDCS improved (i.e., reduced) AB magnitudes for people who had demonstrated robust AB magnitudes at baseline (London & Slagter, 2015). In addition, nonblinkers showed increased spontaneous neural activity in frontoparietal regions at rest, as measured by amplitudes of low frequency fluctuations, whereas blinkers showed increased spontaneous neural activity in occipitotemporal areas and in the cerebellum at rest. Frontoparietal regions are usually implicated in cognitive control, which might suggest that nonblinkers may naturally engage the “right” amount of cognitive control (and subsequently, the “right” amount of attention) for the task at hand.

There are several open questions and potential future directions for this research. Given that people vary in working memory capacity, resting-state attention (e.g., Kounios et al., 2008), or even in selectivity across time (i.e., attentional blink magnitudes), the attentional manipulations used in these studies could affect people differently. In our studies, we did not consider individual differences in baseline working memory capacity, inhibitory or cognitive control, or other executive functions. Thus, it is possible that the manipulations affected people on either end of the spectrum for these measures (e.g., high versus low working memory capacity) differently. Future studies should control for these individual differences, and manipulations could be tailored for each end of the spectrum (e.g., a low cognitive control person could perform an attention task that demands more cognitive control). We were also not able to determine how long the effects of our attentional manipulations last. That is, we cannot know with any certainty that the induced attentional state lasted through the. Given that people can shift their attention rather quickly, future studies could also consider using phasic (i.e., trial-by-trial) attentional manipulations rather than the tonic ones used in Studies 1-3. As previously mentioned, there is a dearth of neuroimaging data that examine whether selective attention or inhibitory control tasks (e.g., central flanker task, Stroop task, and attention to the global level of Navon letters from Studies 1 and 2) activate the same pattern of neural activity or neural correlations as analytic problem solving. Likewise, the relationship between ensemble statistics, distributed attention, and cognitive control still requires investigation. Finally, given that two attention tasks that putatively require distributed attention (i.e., the ensemble statistics task in Study 3 and the rapid object identification task in Wegbreit et al., 2012), it would be interesting to test if insight can be induced by similar tasks that are thought to demand distributed attention (or, at least, do not benefit from selective attention) such as gist perception or visual pop-out tasks (e.g., Treisman, 2006)

In sum, we showed that visual attention tasks can be used to differentially modulate conceptual attention and insight or analytic problem solving. Specifically, tasks that induced less selective or more distributed attention increased subsequent insight problem solving whereas tasks that demanded more selective attention facilitated analytic solving. This body of work extends the current literature, and it provides the groundwork for future studies on the role of selective attention on creative problem solving.

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**Appendix**

Example of Congruent Local-Global Letter stimuli from Study 1

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H       H
H       H
HHHHH
H       H
H       H
```

Example of Incongruent Local-Global Letter stimuli from Study 1

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F       F
F       F
F F F F F
F       F
F       F
```
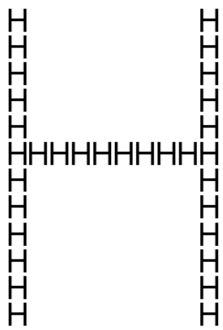
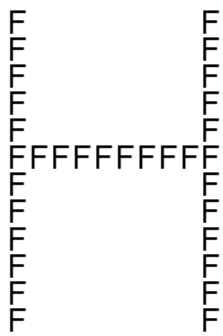
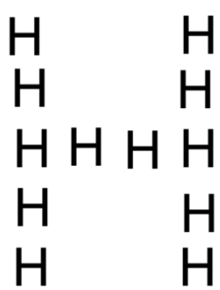

Example of Congruent Global-Salient Letter stimuli from Study 2



Example of Incongruent Global-Salient Letter stimuli from Study 2



Example of Congruent Local-Salient Letter stimuli from Study 2



Example of Incongruent Local-Salient Letter stimuli from Study 2