Title

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Abstract

Research has shown that gesturing can serve to both clarify our thinking and improve our working memory. Working memory capacity (WMC) is widely considered to be a contributing factor in a number of higher order cognitions, including problem solving. The current study investigated the influence of individual differences in WMC, the number of moves required for solution, and the ability to gesture during solution of the Tower of Hanoi. The results show a complex relationship between WMC, problem size and the ability to gesture, and that there are both upsides and downsides to gesturing while problem solving.

Keywords: Problem Solving, Working Memory Capacity, Gesture, Tower of Hanoi.

Introduction

Research has shown that gesturing can serve to both clarify our thinking and improve our working memory (Wagner, Nusbaum, & Goldin-Meadow, 2004). In the present research, we sought to explore the role of gesture in first time problem solving of the Tower of Hanoi (ToH). The ToH task (Simon, 1975) has been used in the cognitive literature as a benchmark cognitive test. It has been used to test a number of higher cognitive abilities, including skill acquisition and transfer (Reber & Kotovsky, 1997), as well to observe developmental changes in cognitive ability and to assess mental deficits in patient populations.

ToH is a complex, yet well-structured problem. Though difficult, its solution space is well-defined. In the classic problem, participants are given three pegs with three differently-sized disks on the first peg. The smallest disk is on top and the largest on the bottom. The goal is to move all disks to the third peg, one disk at a time. In addition, participants are given the constraints that larger disks cannot be placed on smaller disks and that only a top disk can be moved. Even this basic presentation requires at least seven movements to reach the solution.

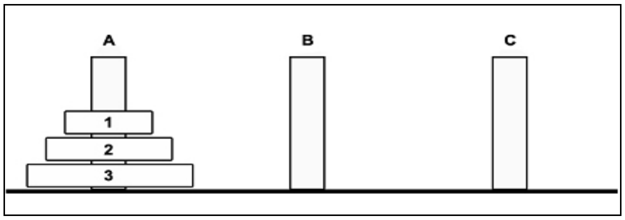

Figure 1. The 3-Disk Tower of Hanoi.

The ToH task is considered complex because it requires the use of multiple processes. First, it requires the creation and maintenance of a problem representation. The representation includes not only the physical objects of the problem (the disks and pegs), but also the task rules, which determine the legality of moves. Errors at the representation level may lead to repeated violations of the rules or memory mistakes related to the positions of disks. Second, the task requires planning. That is, in order to solve efficiently, subjects are required to think ahead, establishing both distant goals (such as the moving of a particular disk to its final location) and immediate subgoals (such as making other moves to open up the opportunity to complete the overarching goal; Anderson, Kushmerick, & Lebiere, 1993). Errors in planning may lead solvers into dead-end movement sequences. Third, efficient solvers need to be able to represent and monitor their progress. It is necessary to keep track of the various objects and subgoals as well as progress through a mental representation of the solution sequence. In addition, solvers must be able to detect errors in planning and correct their mistakes. Errors in monitoring can result in the solver losing track of his or her place, or perseverating on poor moves or movement sequences.

One could imagine that, in complex problem solving (with numerous cognitive processes operating at the same time), capacity limitations may influence problem-solving performance. Working memory capacity (WMC) is a construct that can generally be defined as the ability to retain information in memory while concurrently processing other information (Baddeley, 2002). Differences in WMC have more recently been conceptualized as differences in an attentional-control ability or executive function (Engle, 2002). That is, the ability of a person to perform well on a working memory span task such as reading span or operation span is related to their ability to control or direct their attention (for example, to focus on goal-related stimuli in the face of interference; Conway et al., 2005).

WMC is an important individual difference in cognitive psychology that correlates with numerous measures of cognitive ability (Conway, et al., 2005; Engle, 2002). Researchers have suggested that effective use of working memory is integral to successful problem solving, as the inability to adequately maintain different pieces of information in memory is a significant impairment to problem solving performance (i.e. Kotovsky, Hayes, & Simon, 1985). Additionally, numerous computer models of cognitive activity, including problem solving and skill acquisition, utilize a limited capacity storage component that is analogous to human working memory (Anderson, 1993; Newell & Simon, 1972) in order to fit human performance.

There are a number of reasons why individual differences in WMC should play a critical role in the solution of the ToH. In formulating a problem representation, higher WMC should allow solvers to keep larger numbers of disks in memory. This would allow them to efficiently solve more complex versions of the ToH task (for example, 4-disk variants). Further, there has been some suggestion that WMC may influence a solver's ability to integrate and maintain rules in a problem representation (Kotovsky, Hayes, & Simon, 1985). In planning, higher WMC may allow for the retention of larger numbers of goals and subgoals, leading to faster solving. There has been evidence to support this idea from functional imaging studies that have shown increased activation of the right dorsolateral prefrontal cortex, relative to the planning complexity of a ToH task (Newman, Carpenter, Varma, & Just, 2003) This area has been shown to be associated with working memory capacity and executive functioning. This perspective would lead one to suspect that persons with higher WMC would be more capable of monitoring of their own progress in a mental representation of the solution space.

Surprisingly, the relationship between WMC and performance on the ToH has not yet been demonstrated clearly. The most consistent evidence for the role of working memory in the ToH task comes mainly from studies using a secondary task/load approach. That is, while a participant is attempting to solve a complex problem, he or she is given a separate secondary task to attempt simultaneously (such as remembering the last few digits of a random number sequence). Studies have found that having participants engage in a concurrent task hinders their ability to efficiently solve complex problems (Reber & Kotovsky, 1997), such as the Tower of Hanoi and its isomorphs (Kotovsky & Simon, 1990).

The logic behind these load studies is that the secondary task puts a "load" on working memory, and therefore, when deficits are seen in problem solving, it is attributed to taxing working memory. However, by adding a secondary task, one cannot determine how "normal" problem solving would have proceeded without the additional task and what the role of WMC may be in normal solution processes. A second related problem is that secondary tasks may vary in the extent to which they actually "load" on working memory, and the extent to which they only load on working memory. While many secondary tasks that have been utilized may indeed be demanding, it is less clear that working memory is the only thing that any particular secondary task is affecting. A task intended to tax working memory may be making a problem more difficult for other reasons as well. Thus, deficits associated with secondary task manipulations may not necessarily represent the effects of reduced working memory on problem solving.

Several difficulties with the load approach can be addressed with an individual differences approach using individual performance on complex span tasks, such as reading span and operation span, to assess WMC (Conway et al., 2005), and relating these measures, or a domain-general factor derived from these measures, to an individual's problem solving performance (Ash & Wiley, 2006). Interestingly, the few individual differences studies that have been done on ToH tasks do not show a clear relation with WMC. Some studies using individual difference measures of WMC have shown a relationship with visual/spatial WMC tests (for example, see Zook, Davalos, Delosh, & Davis, 2004). Some studies have failed to find a relationship between WMC and ToH performance, even when using spatial measures of working memory capacity (Welsh, Satterlee-Cartmell, & Stine, 1999). When studies find relationships between ToH and WMC only with spatial and not on other types of working memory measures (i.e. verbal), these results suggest that the relationship between these WMC measures and ToH is due to the spatial components of the tasks rather than to a domain-general WMC component.

There are, however, a few individual differences studies, where some evidence of the expected relationship has been found. Miyake, Friedman, Emerson, Witzki, Howerter, and Wager (2000) demonstrated that performance on a 4-disk variant of the ToH was related to a solver's performance on a number of tasks related to inhibition (including an antisaccade task, and a Stroop task). Zook, Davalos, Delosh, and Davis (2004) have also found performance on Stroop related to performance on ToH. Critically, these tasks have been shown to be related to the domain-general WMC factor derived from multiple WMC tasks (Kane & Engle, 2003).

Another relevant study used the Tower of London, an isomorph of the ToH in which items (in this case, balls) are not moved between columns but moved between holes of different depth (Newman, Carpenter, Varma, & Just, 2003). This study demonstrated a relationship between WMC and brain activation in the frontal cortex during the solving of difficult Tower of London variants. Interestingly, in this study solvers were not allowed to manipulate an external representation of the problem or even gesture (since their motion was necessarily limited within an fMRI). Often, the ToH task is administered using physical objects that can be manipulated in order to solve the problem. By providing manipulable external representations, previous researchers may have been alleviating the load on working memory, and the need to maintain an internal representation of the problem space. This in turn may have eliminated the effects of individual differences in WMC on problem solving in other studies.

For a number of reasons, the ability to gesture or not may be predicted to have an effect on ToH problem solving, as well as on the relationship between WMC and problem solving. Other research has shown that the inability to gesture may worsen performance on complex tasks and increases the amount of working memory load associated with solving (Cary & Carlson, 1999). Gesturing may be a process by which solvers attempt to focus their attention on aspects of the task or keep track of their progress through a problem space. Gesturing has also been linked to improved performance on spatial tasks (Kirsh, 1995); a benefit that ought to influence solution efficiency in the ToH task. And, as suggested above, gesture may help participants to externalize their mental representation and thus free working memory resources.

Garber and Goldin-Meadow (2002) demonstrated that mismatches in speech and gesture patterns during explanation of a solution to the ToH occurred primarily at points where a solver must chose between multiple potential movement paths. Mismatches indicated that gesture was being used to represent solution-related information; in this case, information that was not readily apparent via verbalizations. These findings suggest that both mental representation and gesture are important for resolving an effective strategy.

However, no experiments have directly examined the role of gesture during *first-time* ToH solution attempts. This is especially important because the first solution attempt is also likely to be the one with the highest working memory demand. The goal of the present research was to examine the role of gesturing and individual differences in WMC, and how these might interact, on first time ToH problem solving. The size of the problem space was also varied to examine how this would interact with gesture and WMC as well. The simple predictions were that the ability to gesture, higher WMC and smaller problem spaces should all lead to better performance on the ToH.

Method

Participants

One-hundred and sixteen undergraduates from the University of Illinois at Chicago subject pool were given class credit for participating in this research.

Materials

Practice Problem. Participants were first presented with a practice problem, a two-disk variant of the ToH. The problem required two moves to complete and was intended to familiarize the participant with the movement rules and with how to verbalize their moves while solving.

Tower of Hanoi Problem. Participants saw either a 4-disk unsolved (15-move) or a 4-disk partially-solved (7-move) version of the ToH in paper form. (See Figure 2.) These particular variants allow for the size of the problem space to be manipulated using the same number of objects.

Working Memory Span. Participants received a battery of three working memory span tasks, including Reading Span, Operation Span and Symmetry Span, in a separate session either immediately prior to or immediately following their ToH session. (For information on these span tasks, see Kane et al., 2004.) The main purpose of this battery was to derive a domain-general measure of WMC. Based on Kane, et al. (2004), factor analysis was used to create a factor from the shared variance between the three working memory span tasks. A median split was then performed on this factor to differentiate between high and low-WMC subjects for subsequent analyses.

Procedure

Participants were first given the practice problem to familiarize themselves with the movement rules and verbalizations associated with performing the ToH task. Instructions to the practice task, including movement rules, were given verbally. Participants were allowed to ask any questions, including requesting that the experimenter re-read the movement rules. They were given as long as they needed to complete the practice. After the practice, subjects were presented with the primary ToH task. Before beginning, the rules and goal of the task were reiterated.

Participants were divided into two groups: a gesture and a no-gesture group. In the no-gesture condition, participants received the instructions, “Please refrain from gesturing, whether with your hands or with your head, while solving the problem.” If, during solution, they attempted to gesture, they were instructed to refrain from gesturing. Subjects in the gesture condition received no gesture-related instruction and were allowed to gesture freely.

The participants were given a total of 15 minutes to solve the ToH task. To solve the problem, they stated each move attempt out loud. If at any point the participant made an illegal move, he or she was informed of the fact that they had made an error and had to state a different, legal, move in order to proceed. Alternately, subjects occasionally made memory errors (such as incorrectly recalling the location of a particular disk), which made it impossible to follow their movements. In this case, subjects were told, “I believe that you have made an error,” at which point, the participant was instructed to restart their explanation. Participants who became confused or lost their place could restart the problem at any point during solving, but had to inform the experimenter that he or she was restarting. The session ended when all disks had been moved legally to the rightmost peg, or when the 15 minutes had elapsed.

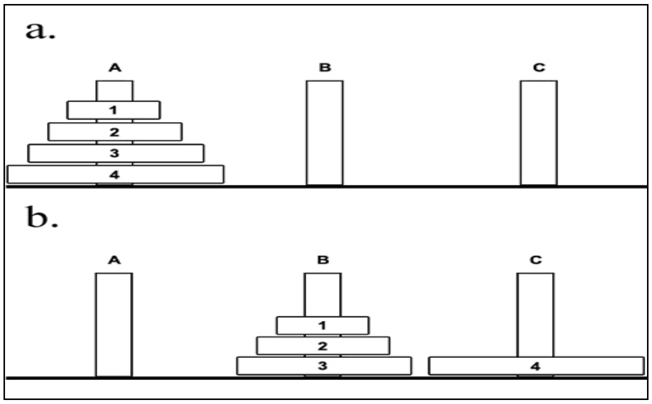

Figure 2. The 15-move (a) and 7-move (b) ToH variants.

Results

Solution Rate

The solution rate for low WMC subjects was not influenced by size of the problem space or by ability to gesture. For all four conditions, low WMC subjects reached the correct solution approximately 90% of the time.

For the high WMC subjects, however, a significant 2-way Gesture x ToH version interaction was found, *F*(1, 58) = 4.00, *MSE* = .22, *p* = .05. High WMC subjects attempted to solve the 15-move ToH, who were *allowed* to gesture, demonstrated the lowest rate of solution (75%). In all three other conditions, high WMC subjects were at ceiling. The unexpected effects that WMC and gesture had on solution rate will be explored in more detail below.

Move Analysis

In order to examine the efficiency of solution for correct solvers, all move attempts were categorized as either legal, illegal, or restart. Illegal moves were any moves attempted that violated the rules of the task. Subjects were corrected if they made illegal moves and had to state a different, legal, move in order to proceed. Restarts were recorded at any point that the solver stated that they were beginning again from the initial problem state.

Legal Moves. As shown in Figure 3, a main effect was found for problem size, *F*(1, 91) = 71.29, *MSE* = 8572.85, *p* < .01. As expected, 7-move problems were solved in fewer moves than 15-move problems. However, the expected overall effects for gesture and WMC were not found. Instead, there was a 3-way WMC x Gesture x Problem Size interaction, *F*(1, 83) = 5.50, MSE = 661.15, *p* = .02. High WMC solvers showed the predicted benefit from the ability to gesture while solving the 15-move variant of the ToH. However, high WMC solvers demonstrated *poorer* performance in the 7-move variant when allowed to gesture. Low WMC solvers did not seem to benefit from the ability to gesture at either problem size.

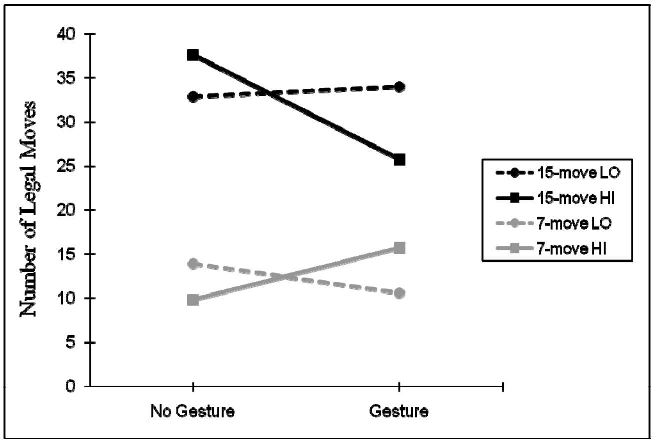

Figure 3. The effects of Gesture, WMC & Problem Size on the number of legal moves made to reach solution.

Illegal moves. Illegal move attempts represent a failure in either the representation or the monitoring of the solution process. Excessive illegal move attempts indicate that the subject either has forgotten the rules to the problem or is no longer monitoring their attempted moves for legality.

No main effects were found for illegal moves. As shown in Figure 4, a marginal 3-way WMC x Gesture x ToH Version interaction was found, *F*(1,83) = 24.48, *MSE* = 3.00, *p* = .09. Low WMC solvers demonstrated the expected benefit from being able to gesture, attempting fewer illegal moves in both the 15 and 7-move ToH. High WMC solvers, however, showed the expected benefit in only the 15-move version. In the 7-move version, high WMC solvers attempted *more* illegal moves when allowed to gesture.

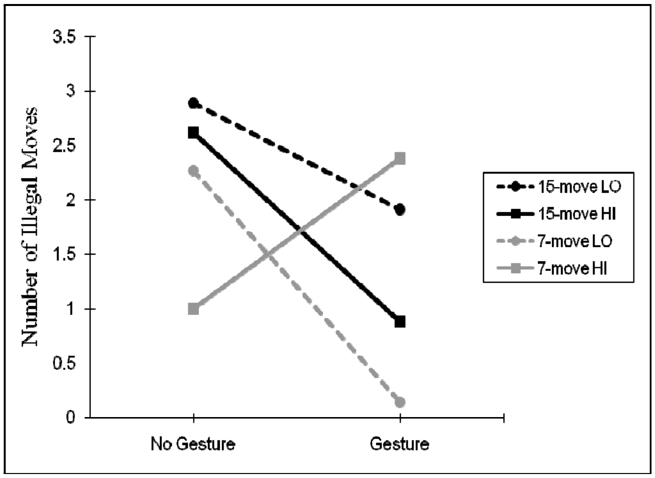

Figure 4. The effects of Gesture, WMC & Problem Size on the number of illegal moves attempted during solution.

Restarts. Restarts occur when subjects feel as if they are lost, when they have forgotten their solution strategy or their current problem state. Alternately, restarts may occur when the subjects can see no benefit from continuing on their current path. Repeated restarts can be indicative of perseveration on inefficient or difficult movement patterns or strategies.

No main effects were observed for restarts, but a 3-way WMC x Gesture x ToH Version interaction was again found, *F*(1, 83) = 27.02, *MSE* = 5.36, *p* = .02 (see Figure 5). Low WMC solvers with the 7-move version and high WMC solvers with the 15-move version demonstrated the expected benefit of gesture in reducing the need to restart, while low WMC solvers with the 15-move version did not appear to benefit due to gesture. Interestingly, a deficit was again found for 7-move, high WMC solvers, as the ability to gesture resulted in *more* restarts.

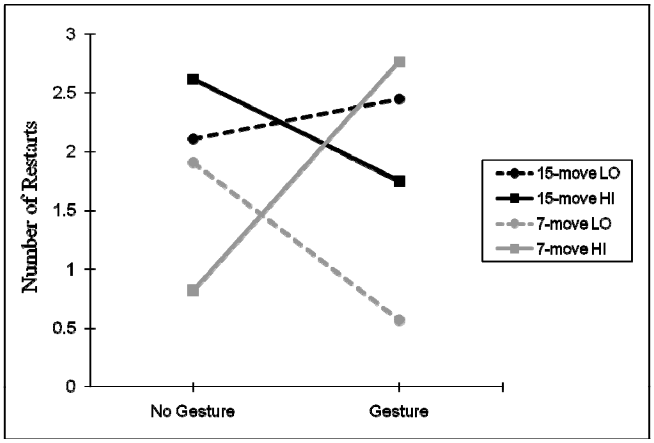

Figure 5. The effects of Gesture, WMC & Problem Size on the number of restarts made during solution.

Discussion

In total, these results suggest a more complicated relationship between gesture, working memory capacity and problem solving than one might initially expect. For many solvers, gesturing played the supporting role that had been predicted, preventing illegal moves and reducing the need to restart during solving.

However, in the case of many high WMC subjects, the ability to gesture hindered performance. Not only was the lowest rate of solution in the problem found for these subjects in the 15-move ToH version, but a consistent pattern of poorer performance on their part was found for the 7-move version.

These results illuminate the inconsistent findings in the literature on the relationship between WMC and ToH performance, as performance of high and low working memory solvers appeared to vary drastically based on certain aspects of the presentation of the problem – specifically the size of the problem space and the ability to gesture. Interactions such as the ones found in this experiment suggest that WMC may influence problem solving performance in a number of ways, and the story is not as simple as the prediction that higher WMC or lower "load" will translate to better performance.

Further, these findings are similar to other results that have recently shown deficits for high WMC participants in a number of problem solving situations (Beilock & deCaro, 2007; Ricks, Turley-Ames & Wiley, 2007). Suggested reasons for these deficits are the ability of high WMC solvers to focus their attention on specific aspects of the problem (Ricks, Turley-Ames & Wiley, 2007), or the ability of high WMC solvers to carry out computationally expensive solution strategies, which may prevent high WMC solvers from finding more elegant solutions (Beilock & deCaro, 2007). The ability to focus ones' attention can often be a good thing, but in some cases, it can lead to fixation on an incorrect solution path, or a failure to consider other strategies for solution.

The complementary explanations of fixation or perseveration in ineffective strategies seem to be able to explain the unexpected effects of gesture on the high WMC solvers. When given the opportunity to gesture on the easier problem, it appears that the high WMC solvers were more likely to use and perseverate on a "trial and error" strategy. The increased number of illegal movement errors for these solvers speaks to the use of such a strategy. Further, the increased number of restarts suggests that progress toward solution was not deliberate, or planned, but rather haphazard and halting. Yet, in conditions where the problem space increased or gesturing was not allowed, then high WMC were able to use more effective strategies for solution.

We are currently completing a protocol and gesture analysis to explore strategy use, perseveration, and the use of gesture more directly. Some interesting questions to be explored are how the participants in the gesture condition used gestures, when they used them, what kinds of gestures they used, and if different types of gestures were more or less effective for problem solving performance. It will be especially informative to compare these observations of gesture use during a first ToH problem solving attempt, with the observations of Garber and Goldin-Meadow (2002) who performed a similar analysis on later ToH attempts. Another direction for future analyses is to examine the relation of the different domain-specific WMC measures on ToH performance, and particularly how spatial WMC interacts with the ability to gesture or the size of the problem space.

At present the results are highly convergent with Beilock and DeCaro (2007) who found high WMC solvers were *less* likely than low WMC solvers to notice a more efficient solution path on a waterjugs task. In that study, when high WMC solvers were put under pressure (similar to our problem space and gesture manipulations), then high WMC solvers did use the shortcuts.

Further, these findings are also reminiscent of work that has been exploring the mixed effects of concrete representations on learning and problem solving. A similar tension has been found such that concreteness may support faster initial learning or problem solving, but it can work against transfer (Goldstone & Son, 2005; Schwartz, 1995; Sloutsky, Kaminski & Heckler, 2005). Like concreteness, the ability to gesture may be preventing some students from engaging in more effortful, but ultimately more useful abstract thinking.

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