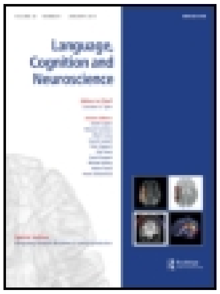

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Gesturing has a larger impact on problem-solving than action, even when action is accompanied by words

Caroline Trofatter[a], Carly Kontra[a], Sian Beilock[a] & Susan Goldin-Meadow[a]

[a] Department of Psychology, The University of Chicago, 5848 South University Avenue, Chicago, IL 60637, USA

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Caroline Trofatter*, Carly Kontra, Sian Beilock and Susan Goldin-Meadow

Department of Psychology, The University of Chicago, 5848 South University Avenue, Chicago, IL 60637, USA

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The coordination of speech with gesture elicits changes in speakers' problem-solving behaviour beyond the changes elicited by the coordination of speech with action. Participants solved the Tower of Hanoi puzzle (TOH1); explained their solution using speech coordinated with either Gestures (Gesture + Talk) or Actions (Action + Talk), or demonstrated their solution using Actions alone (Action); then solved the puzzle again (TOH2). For some participants (Switch group), disc weights during TOH2 were reversed (smallest = heaviest). Only in the Gesture + Talk Switch group did performance worsen from TOH1 to TOH2 – for all other groups, performance improved. In the Gesture + Talk Switch group, more one-handed gestures about the smallest disc during the explanation hurt subsequent performance compared to all other groups. These findings contradict the hypothesis that gesture affects thought by promoting the coordination of task-relevant hand movements with task-relevant speech, and lend support to the hypothesis that gesture grounds thought in action via its representational properties.

Keywords: gestures; action; problem-solving; mental representations; speech; embodied cognition

People often use their hands when they speak – they gesture. There is ample evidence that the production of these gestures reflects thought (Alibali, Bassok, Solomon, Syc, & Goldin-Meadow, 1999; Cook & Tanenhaus, 2009; Garber & Goldin-Meadow, 2002), predicts changes in thought (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry, Church, & Goldin-Meadow, 1988; Ping, Larson, Decatur, Zinchenko, & Goldin-Meadow, 2014) and even elicits changes in thought (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007; Goldin-Meadow, Cook, & Mitchell, 2009; Goldin-Meadow et al., 2012; Singer & Goldin-Meadow, 2005).

As an example, the gestures learners produce when they explain their solutions to a math problem predict how likely they are to profit from instruction in that problem (Perry et al., 1988); similar effects are found on conservation problems (Church & Goldin-Meadow, 1986), balance scale problems (Pine, Lufkin, & Messer, 2004) and stereochemistry problems (Ping et al., 2014; for review, see Goldin-Meadow & Alibali, 2013). Moreover, encouraging learners to produce particular gestures during a math lesson makes it more likely that the learners will add the problem-solving strategy instantiated in those gestures to their spoken repertoires (Goldin-Meadow et al., 2009), and will remember what they learned during the lesson (Cook, Mitchell, & Goldin-Meadow, 2008). Similarly, the types of gestures learners produce on a mental rotation task are correlated with their success on the task (Ehrlich, Levine, & Goldin-Meadow, 2006), and encouraging gesture on mental rotation problems leads to improved performance in both adults (Chu & Kita, 2011) and children (Goldin-Meadow et al., 2012). Despite the widespread evidence that gesturing is linked to thinking, the mechanism(s) driving this link is unclear.

One theory holds that gesture production allows action information to merge with a speaker's mental representations (Goldin-Meadow & Beilock, 2010; Hostetter & Alibali, 2008). Importantly, under this view, gestures are not synonymous with actions. Gestures are a form of action in that they are movements produced by the hand; moreover, those movements often reflect detailed aspects of the speaker's action experiences (e.g., Cook & Tanenhaus, 2009). But gesture and action are distinct phenomena – action can have a direct impact on the world, whereas gesture affects the world indirectly by representing information that listeners can apprehend (Goldin-Meadow, 2003; Goldin-Meadow & Sandhofer, 1999). In this sense, gesture is a unique form of action, one that can influence thought through its representational properties. Indeed, gesture has been found to promote transfer of knowledge better than action (Novak, Congdon, Hermani-Lopez, & Goldin-Meadow, 2014) suggesting that the beneficial effects gesture has on learning may reside in the features that differentiate it from action.

However, gesture differs from action not only in how it affects the world (indirectly rather than directly), but also in its relationship to speech – actions tend to be performed without relevant co-occurring speech, whereas

*Corresponding author. Email: lalaith@uchicago.edu

gestures are, by definition, coordinated with speech (McNeill, 1992). The close relationship between gesture and speech has been established both theoretically and empirically, and this close relationship could be argued to be the mechanism by which gesture affects thought. Theoretically, most modern gesture theories assume a robust relationship between gesture production and language processes. For example, the interface hypothesis (Kita & Ozyurek, 2003; Kita et al., 2007) suggests that gesture and speech are interactively coordinated during language production, and the integrated systems hypothesis (Kelly, Ozyurek, & Maris, 2010) suggests that this relationship holds for language comprehension and that the interaction between gesture and speech is bidirectional and obligatory. As another example, the Gestures as Simulated Action framework (Hostetter & Alibali, 2008) postulates that the production of representational gestures occurs when the oral-manual activation of speech production is integrated with the simulated action involved in message conceptualisation. Finally, the growth point hypothesis (McNeill & Duncan, 2000) holds that gesture and its synchronous speech are components of a dialectic and merge into minimal units called 'growth points'. In this model, growth points are 'material carriers' of thinking, and speech and gesture *together* are the joint embodiment of thought – together they 'bring thinking into existences as modes of cognitive being' (McNeill & Duncan, 2000). Under this view, gesture does not, on its own, affect thinking – it is only through its interactions with the language system during communication that gesture has an impact on thought.

Empirically, the close relationship between gesture and language can be seen in typically developing infants as young as six months for whom canonical babbling is linked to the onset of rhythmic hand banging (Ejiri & Masataka, 2001; Iverson & Thelen, 1999). Throughout development, vocabulary comprehension, labelling, word combinations and grammatical production all have reliable gesture correlates (see Bates & Dick, 2002, for a review), and early gesture, when analysed in relation to the speech it accompanies, can predict the onset of two-word speech (Iverson & Goldin-Meadow, 2005) and the acquisition of different types of sentences and elaborations (Cartmill, Hunsicker, & Goldin-Meadow, 2014; Ozcaliskan & Goldin-Meadow, 2005).

Given the extensive theoretical and empirical support for the tight link between gesture and speech, it is possible that gesture's influence on thought could simply be due to the relationship it holds to speech (rather than to its representational properties). In other words, it could be that gesture's power to affect behaviour is a function of its coordination with speech – language together with movement may be a more powerful tool than language alone or movement alone. We explore this possibility by revisiting a problem-solving task on which gesture has been found to exert a more powerful influence than action – Tower of Hanoi (TOH; Beilock & Goldin-Meadow, 2010; Goldin-Meadow & Beilock, 2010; Kontra, Goldin-Meadow, & Beilock, 2012). The gestures one group of participants produced while explaining their TOH solutions (which were, of course, produced with speech) had a bigger impact on their subsequent performance than did the actions another group of participants produced while demonstrating their TOH solutions – importantly, the actions were all produced *without* speech. We have interpreted this finding as evidence that the impact of gesture stemmed from its representational properties; however, an alternative interpretation could be that the impact of gesture stemmed from its close relationship to speech. The crucial missing comparison needed to settle this issue is action produced and coordinated with speech. In the next section, we describe previous work investigating gesture's impact on problem-solving in the context of TOH, which sets the stage for the current study.

Previous studies of gesture and the TOH problem-solving task

In support of the hypothesis that gesture changes thought by grounding it in action, Beilock and Goldin-Meadow (2010; see also Goldin-Meadow & Beilock, 2010) showed that the information participants convey through their gestures about the weight of an object influences how they subsequently interact with that object. When gesturing, one must use either one or two hands – using one hand to represent moving an object implicitly signals that the object is relatively light, using two hands signals that the object is heavy. Undergraduate students solved a four-disc TOH1 task, and then explained how they solved the task using gesture along with speech (Gesture condition). In the final step, participants solved the TOH2 task again (TOH2). In TOH1, the size of the discs was positively correlated with their weight – the smallest disc was the lightest and could easily be lifted with one hand; the largest disc was the heaviest and required two hands to lift. At TOH2, half of the participants in each condition were assigned to the Switch group, and the other half were assigned to the No-Switch group. Participants in the No-Switch group solved TOH2 using the same TOH1 discs, but participants in the Switch group solved TOH2 using discs with reversed weights – the smallest disc was now the heaviest and could not be lifted with one hand.

Participants in the Gesture Switch group performed significantly worse on TOH2 (in terms of both number of moves and amount of time taken to solve the problem), compared to participants in the Gesture No-Switch group. Moreover, the more often a participant gestured about the smallest disc with one hand during the explanation, the worse that participant did on TOH2 (Beilock & Goldin-Meadow, 2010). Importantly, this effect was found only in the Gesture condition – when the study was repeated without the explanation segment, the participants (who did not gesture between TOH1 and TOH2) performed equally well on TOH2 in both the Switch and No-Switch groups, even if they had previously used one hand to lift the smallest disc during TOH1. In other words, gesturing about the smallest disc with one hand during the explanation phase of the study had an impact on subsequent performance, whereas acting on the smallest disc with one hand during TOH1 did not.

This finding was replicated and extended by Goldin-Meadow and Beilock (2010). They again asked adults to solve TOH twice. In this study, as in Beilock and Goldin-Meadow's (2010) study, after solving TOH1, one group of adults was asked to explain how they solved the task; this group gestured about moving the discs (Gesture condition). A second group was asked to demonstrate the task (rather than talk about solving the task) after solving TOH1; this group physically moved the discs (Action condition). This protocol thus directly contrasts gesture and action. Participants in both conditions then solved TOH2; half were in the Switch group and half were in the No-Switch group. If using one hand to either gesture about or act on the small disc serves to enforce a representation of the small disc as light (i.e., able to be lifted with one hand), then switching disc weights at TOH2 should hurt performance equally in both the Gesture and Action conditions. In other words, if action works in the same way as gesture to solidify information in one's mental representation, then performance in the Action and Gesture groups ought to be identical – when the disc weights are switched, performance should drop. However, Goldin-Meadow and Beilock (2010) found that the impact of switching weights for the Action condition was significantly less than the impact of switching weights for the Gesture condition. These findings suggest that gesturing about actions influences how information is mentally represented and, in this instance, affects problem-solving more than repeatedly performing the actions themselves.

Gesture thus appears to be a special form of action with the power to influence thought, perhaps because of its representational nature. However, the fact that participants in the Gesture condition spoke while moving their hands, whereas participants in the Action condition moved the discs silently, leaves open the possibility that it is the coordination of speech with action – be it representational or not – that solidifies information in mental representations. The current study was designed to explore this possibility.

Current study

The current study investigates whether action has as powerful an effect on problem-solving as gesture when it too is produced along with speech. We ask here whether switching disc weights has a detrimental effect on performance at TOH2 when participants speak as they *act* on the puzzle, just as it does when participants speak as they *gesture* about the puzzle. Such a finding would support the theory that the coordination of movement with speech is driving gesture's impact on learning, rather than the representational nature of gesture per se.

In the current study, we included the Gesture and the Action conditions reported in Goldin-Meadow and Beilock's (2010) study, and added a condition in which participants were asked to explain their solutions while physically solving the puzzle (Action + Talk). The original finding suggests that gesturing about the puzzle (Gesture + Talk) will lead to different subsequent behaviour, compared to performing puzzle-related actions (Action). If gesture differs from action because it affords the coordination of task-relevant speech with task-relevant movements, then producing concrete actions together with speech (Action + Talk) should affect behaviour in the same way as gesture (Gesture + Talk); that is, performance should decline in both conditions after the disc weights are switched. If, however, gesture differs from action because representational movements made about physical objects lead to differences in the mental representations of those objects, then coordinating concrete actions with speech (Action + Talk) should have the same effect on subsequent performance as performing the concrete actions silently (Action); that is, performance in both action conditions should be unaffected by the switch in disc weights.

Method

Participants

Sixty University of Chicago undergraduate students (M = 20.41 years; range = 18.3–25.2 years), 21 males, received either course credit or financial compensation for participating in a 'Problem Solving Study'.

Materials

The TOH apparatus consists of three evenly spaced vertical wooden pegs (18″ tall, 0.5″ in diameter) mounted on a rectangular wooden base (1″ tall, 4″ wide and 1″ deep). For all conditions, four smooth white discs (size and weight positively correlated) were initially stacked on the leftmost peg, and could slide on and off each peg (see Figure 1).

The discs are constructed from vinyl phonograph records and strips of vinyl sheeting, and were painted with several thick coats of white outdoor paint to be smooth and shiny. The weights of the TOH1 discs for all participants were as follows: smallest disc A = 0.8 kg; disc B = 1.6 kg; disc C = 2.3 kg; and largest disc D = 2.9 kg. For participants solving TOH2 in the Switch condition, a

Figure 1. TOH board and discs.

second set of discs (smallest disc A is heaviest) was substituted and weighed as follows: smallest disc A = 2.9 kg; disc B = 2.3 kg; disc C = 1.6 kg; and largest disc D = 0.8 kg.

Task and rules

Participants gave informed consent and were asked to solve the TOH puzzle. The goal is to move the discs from the start peg to the end peg while following two rules: move only one disc at a time and never put a larger disc on top of a smaller disc. All participants initially practiced solving variations of the puzzle to ensure familiarity with the rules and the apparatus.

Procedure

Each participant then solved the four-disc puzzle while pretest measures of solution time and number of moves were recorded (TOH1). Previous studies using this version of the TOH task (Beilock & Goldin-Meadow, 2010; Goldin-Meadow & Beilock, 2010) have established that participants who solved TOH1 in less than 65 seconds are at ceiling and have very little room to improve task performance. Since we were interested in the possibility that participants may become better or worse from TOH1 to TOH2, we included in the 60 participants only those who solved TOH1 in more than 65 seconds (28 participants were ineligible to complete the study based on these criteria). After solving TOH1, each participant demonstrated her solution to a confederate using either concrete actions alone (Action), concrete actions and speech (Action + Talk) or gesture and speech (Gesture + Talk; see Figure 2).

Participants were led to believe that the confederate was a participant in another experimental condition who would go on to attempt the task herself. Participants in the Action condition were asked to demonstrate their solution but not speak to the confederate. To prevent participants in the Action + Talk condition from interrupting their actions to gesture about the task, they were asked not to use their hands except to move the discs. Only three participants in the Action + Talk condition gestured about the discs during the explanation phase, and were immediately reminded to make only disc movements with their hands.

Figure 2. Diagram of explanation phase.

Participants in the Gesture + Talk condition were encouraged to use their hands during their explanations, although pilot testing revealed that people gesture readily in this context even without a direct prompt. Participants in all three groups were then escorted to another room and asked to complete a visualisation of viewpoints task (Guay, 1976). This task was timed, and no participant took longer than eight minutes (M = 5.3 min, SE = 0.48 min). Finally, each participant returned to the original room and solved the puzzle a final time at post-test (TOH2), using either the original discs with positively correlated size and weight (No-Switch) or a new set of discs with negatively correlated size and weight (Switch; see Figure 3).

Note that the smallest disc A in the No-Switch set can easily be lifted and moved with one hand, but the smallest disc A in the Switch set is too heavy and requires two hands to move successfully. One participant was dropped from analysis because his hands were large enough and he was strong enough to lift the Switch disc A with one hand (he could therefore choose whether to lift the disc with one or two hands). A second participant was dropped from analysis because she reported (in response to the question asked of all participants during debriefing – 'have you ever solved a puzzle like this before?') that she had had recent, in-depth experience reasoning about the TOH puzzle during an algorithms class. No participant was initially aware that the discs had been switched, as the Switch discs looked just like the No-Switch discs, and the discs had been covertly replaced while participants were

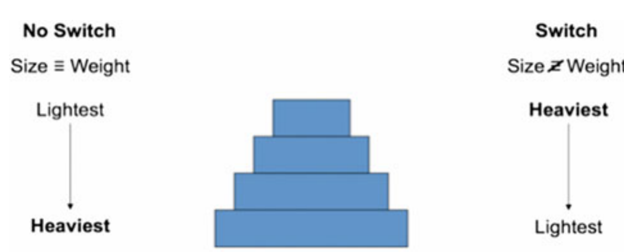

Figure 3. Diagram of discs for No-Switch and Switch TOH2 discs.

engaged in another task outside the room. At the end of the experiment, participants were thanked and debriefed.

Results

The dependent measure of interest (as in both Beilock & Goldin-Meadow, 2010, and Goldin-Meadow & Beilock, 2010) was the change in solution time from pretest to post-test, that is, time to solve TOH1 subtracted from time to solve TOH2 for each individual. Change in solution time was highly correlated with change in number of moves to solution ($r = 0.88$, $p < 0.001$). The results for both measures are displayed in Figure 4.

There was a significant 3 (condition: Action, Gesture + Talk, Action + Talk) × 2 (group: No-Switch, Switch) interaction for both time, $F(2, 52) = 3.26$, $p < 0.05$, and number of moves, $F(2, 52) = 4.85$, $p < 0.02$. Post hoc (Tukey–Kramer) comparisons with an alpha level of 0.05 indicated no significant differences between the Action Switch and Action No-Switch groups, nor between the Action + Talk Switch and Action + Talk No-Switch groups (for either time or number of moves). Collapsing across the Switch and No-Switch groups, participants in the Action condition solved TOH2 more quickly than TOH1 ($M_{TOH2–TOH1} = -40.00$ s, $SE = 10.29$ s, $t(17) = 3.89$, $p < 0.002$), and with fewer moves than TOH1 ($M_{TOH2–TOH1} = -6.33$, $SE = 1.23$, $t(17) = 5.14$, $p < 0.0001$), as did participants in the Action + Talk condition, both for time ($M_{TOH2–TOH1} = -45.75$ s, $SE = 8.09$ s), $t(19) = 5.65$, $p < 0.0001$, and for moves ($M_{TOH2–TOH1} = -8.95$, $SE = 2.00$), $t(19) = 4.47$, $p < 0.0004$. Thus, participants in both Action conditions (i.e., with Talk and without it) improved over time, regardless of whether TOH2 was performed on the original or the switched-weight discs.

In contrast, although the Gesture + Talk No-Switch group improved with practice for time ($M_{TOH2–TOH1} = -28.00$ s, time $SE = 7.00$ s), $t(8) = 4.00$, $p < 0.004$, and for moves ($M_{TOH2–TOH1} = -4.67$, $SE = 2.19$), $t(8) = 2.13$, $p = 0.065$, the Gesture + Talk Switch group experienced a *decline* in performance from TOH1 to TOH2; that is, they spent more time on TOH2 than TOH1 ($M_{TOH2–TOH1} = 35.27$ s, $SE = 17.80$ s), $t(10) = 1.98$, $p = 0.076$, and produced more moves on TOH2 than TOH1 ($M_{TOH2–TOH1} = 5.82$, $SE = 2.86$); $t(10) = 2.03$, $p = 0.069$. Post hoc (Tukey–Kramer) comparisons with an alpha level of 0.05 revealed significant differences between the Gesture + Talk Switch group and the Gesture + Talk No-Switch group for time ($p < 0.03$) and for moves ($p < 0.05$), as well as between the Gesture + Talk Switch group and all four of the Action groups, both for time and for moves (all p-values < 0.05). Performance suffered only for participants who gestured about their solution and then solved TOH2 with switched discs; performance improved for participants who gestured and then solved TOH2 with the original set of discs[1] and for participants who acted and then solved TOH2 with either the original or switched set of discs.

We also asked whether the representational content of participants' gestures influenced TOH2 performance (see Figure 5). In previous work (Beilock & Goldin-Meadow, 2010; Goldin-Meadow & Beilock, 2010), we found that the greater the percentage of one-handed gestures a participant produced during the explanation phase, the larger that participant's subsequent drop in performance from TOH1 to TOH2. In the current study, we find a

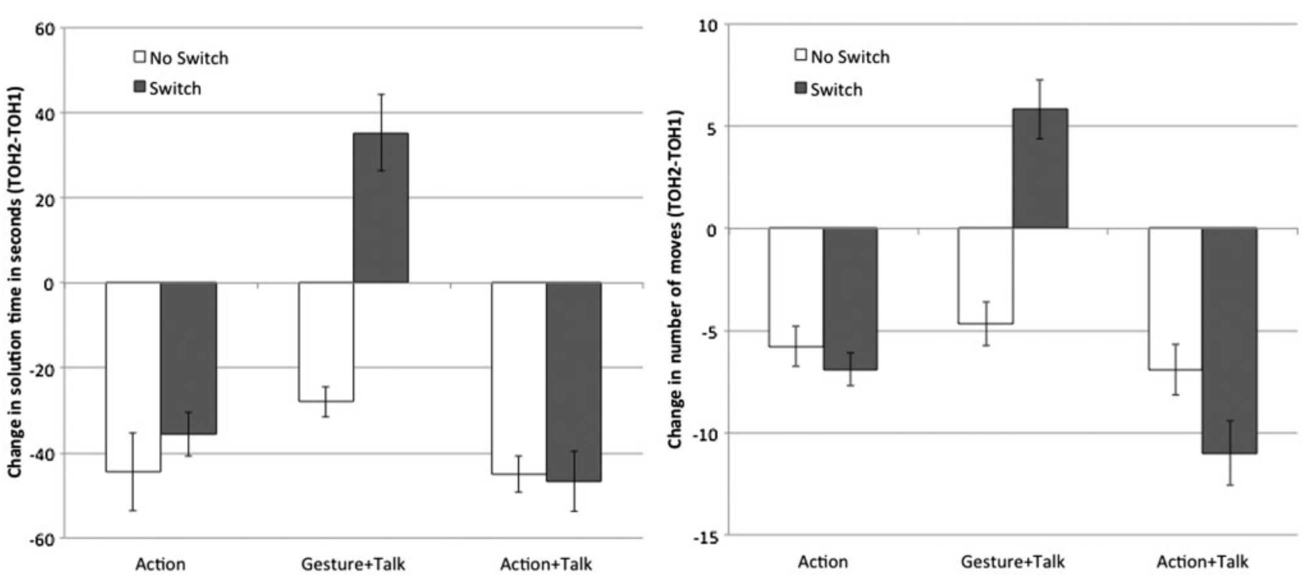

Figure 4. Difference (TOH2 – TOH1) in solution time (left) and number of moves (right) as a function of condition (Action, Gesture + Talk, Action + Talk) and group (Switch, No-Switch).

non-significant trend in this direction for the Gesture + Talk Switch group (n = 11) for both solution time (see Figure 5 left graph; r = 0.41, p = 0.21) and number of moves (not shown; r = 0.37, p = 0.26).[2]

Although we did not have sufficient statistical power to find a significant correlation within the Gesture + Talk Switch group, we did find that the relation between one-handed movements and change in performance from TOH1 to TOH2 was significantly different for the Gesture + Talk Switch group compared to all other groups. When we regressed percentage of one-handed movements (gestures or actions) about the smallest disc, group (Gesture + Talk Switch group versus all five other groups combined), and the interaction (percentage of one-handed movements × group) on change in solution time (or moves) from TOH1 to TOH2, we found a significant interaction between group and percentage of one-handed movements for change in solution time, β = 0.43, t = 2.07, p < 0.05. The same interaction was marginal for change in moves to solution, β = 0.38, t = 1.78, p = 0.081. The correlations displayed in the left and right panels of Figure 5 are thus significantly different from one another, demonstrating that the relation between one-handed movements and subsequent TOH performance depended on the group – more frequent one-handed movements about the smallest disc was positively related to change in performance from TOH1 to TOH2 in the Gesture + Talk Switch group (r = 0.41), but not in the other five conditions combined (r = −0.15).

Importantly, there were no significant differences between the mean percentage of one-handed movements about/on the smallest disc as a function of condition or group: A 3 (condition: Action, Gesture + Talk, Action + Talk) × 2 (group: No-Switch, Switch) analysis of variance revealed no main effect of either condition or group, F's < 1, and no interaction, $F(2, 52)$ = 1.88, p = 0.16. Thus, the differences we found in TOH2 performance across the groups cannot be due to the number of one-handed movements produced per se. These movements have an impact on subsequent performance only when they are used representationally (in the Gesture + Talk condition), and only when the information conveyed has the potential to conflict with subsequent performance (Switch group).

Given that our goal was to determine whether gesture's impact on problem-solving stemmed from the fact that it was produced along with speech, we also analysed the speech produced by participants in the Gesture + Talk and Action + Talk conditions. Participants in both Talk conditions spent approximately the same amount of time explaining their solutions (Gesture + Talk: M = 190.60 s, SE = 20.25 s; Action + Talk: M = 134.30 s, SE = 14.03 s),[3] and described the same number of moves during their explanations (Gesture + Talk: M = 21.95, SE = 1.46, Action + Talk: M = 23.6, SE = 2.19). However, participants in the Gesture + Talk condition used a greater number of words per move (M = 17.43, SE = 1.22) than participants in the Action + Talk condition (M = 11.96, SE = 1.11), $F(1, 38)$ = 10.998, p < 0.003. In addition, and not surprisingly given that the discs were present in the Action + Talk condition but not in the Gesture + Talk condition, participants in the two conditions differed in how often, and how explicitly, they referred to the discs.

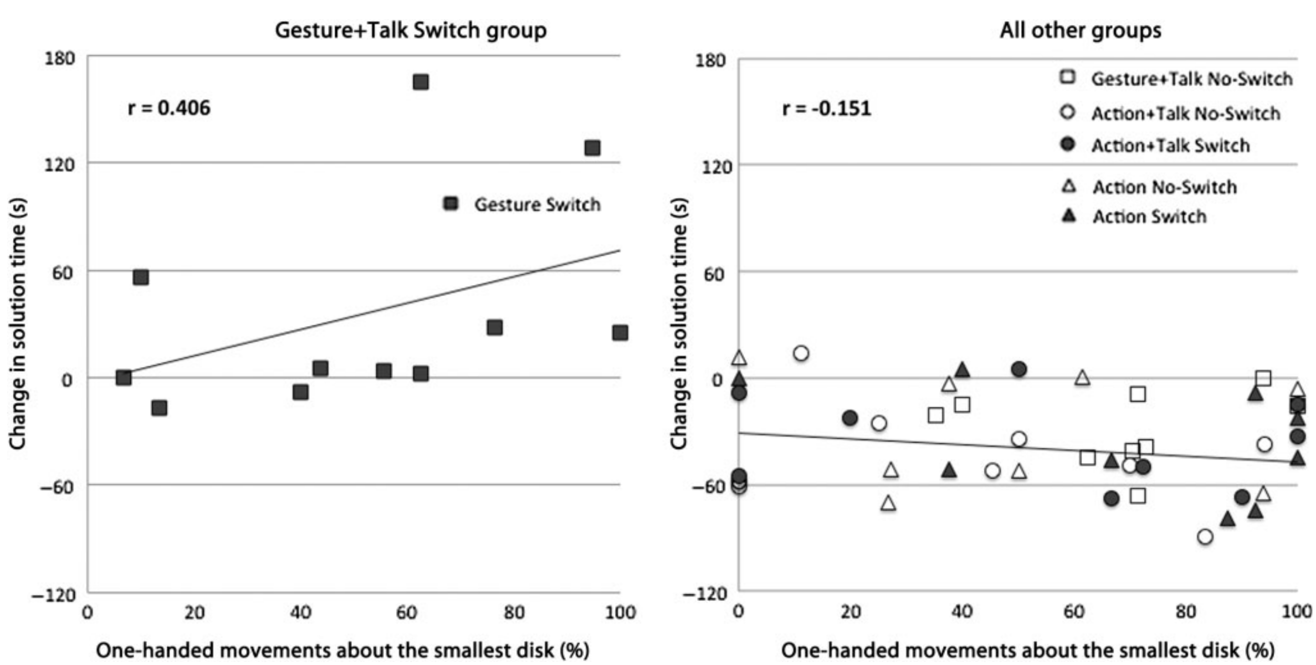

Figure 5. Change in time to solution of TOH problem for all conditions as a function of percentage of one-handed gestures about, or actions on, the smallest disc A during the explanation phase.

Overall, participants in the Gesture + Talk condition referred to the discs 933 times, and 77% of those references mentioned a specific attribute of the disc (e.g., 'the smallest one', 'this bottom disc', 'disc number three', 'the one from before'); the remainder of their references were deictic ('that one', 'this', 'that disc', 'it', 'the other one'). In contrast, participants in the Action + Talk condition referred to the discs 514 times, and only 47% of their references were specific.

It is important to note, however, that these differences in amount and type of speech cannot account for the pattern of results seen in Figure 4. Participants in the Gesture + Talk Switch group performed significantly worse on TOH2 than participants in the Gesture + Talk No-Switch group yet these two groups referred to the discs equally often (2.16 average disc references per utterance for Gesture + Talk Switch versus 2.08 average disc references per utterance for Gesture + Talk No-Switch) and an equal percentage of their disc references were specific (73% for Gesture + Talk Switch versus 80% for Gesture + Talk No-Switch). Moreover, participants in the Gesture + Talk No-Switch group performed no differently from participants in the two Action + Talk groups (Switch and No-Switch), yet they produced more references to the discs than the Action + Talk groups (421 total disc references for Gesture + Talk No-Switch versus 243 total disc references for Action + Talk Switch, 271 total disc references for Action + Talk No-Switch) and more of their references were specific (80% for Gesture + Talk No-Switch versus 51% for Action + Talk Switch, 42% for Action + Talk No-Switch). Thus, although there were differences in the speech that accompanied gesture versus action, those differences cannot explain the fact that gesturing had a bigger impact on problem-solving than action.

Participants in the Gesture + Talk conditions used more specific speech than participants in the Action + Talk conditions, but they did not use more specific terms referring to weight – in fact, none of the participants in any of the conditions referred to weight in their speech. But weight was encoded in gesture. In this regard, it is important to note that our participants were not encoding size in their gestures. We coded the diameter of all gestures referring to the smallest disc. If these gestures encoded information about the size of the disc, then the diameter of one-handed gestures referring to the smallest disc (measured on video from the widest distance between the index fingertip and thumbtip) should, on average, be smaller than the diameter of two-handed gestures referring to the smallest disc (measured on video from the widest distance between the two adductor pollicis muscles). We found no evidence for this prediction: In the Gesture + Talk condition (both Switch and No-Switch), the diameter of one-handed gestures referring to the smallest disc (n = 198, M = 2.03 cm, SE = 0.11) was not significantly different from the diameter of two-handed gestures referring to the smallest disc (n = 127, M = 2.11 cm, SE = 0.15) (t = 0.44, p = 0.66). These gestures thus seem to encode disc weight rather than disc size.

But size is highly correlated with weight. Perhaps when participants mentioned size in speech, they activated implicit ideas about weight, and it is those implicit ideas (rather than the implicit ideas encoded in gesture) that produced the patterns found in Figures 4 and 5. If so, the more participants used words like 'small', 'little' and 'tiny' to refer to the smallest disc during the explanation period, the worse they ought to perform on TOH2 in the Switch conditions, but not in the No-Switch conditions. We found no evidence for this prediction: the correlation between the percentage of size words referring to the smallest disc (i.e., number of size words referring to the smallest disc out of total references to the smallest disc) and change in solution time from TOH1 to TOH2 was $r = -0.11$, $p = 0.38$, in the Gesture + Talk Switch condition; $r = -0.29$, $p = 0.19$, in the Gesture + Talk No-Switch condition; $r = -0.34$, $p = 0.18$, in the Action + Talk Switch condition; and $r = -0.36$, $p = 0.15$, in the Action + Talk No-Switch condition. We found the same non-effect for change in number of moves from TOH1 to TOH2: $r = -0.33$, $p = 0.16$, in the Gesture + Talk Switch condition; $r = -0.03$, $p = 0.47$, in the Gesture + Talk No-Switch condition; $r = 0.02$, $p = 0.48$, in the Action + Talk Switch condition; and $r = 0.07$, $p = 0.42$, in the Action + Talk No-Switch condition. None of the pair-wise comparisons was significantly different from one another (all p's > 0.40). Participants' use of size words cannot account for the effect seen in Figure 4.

As a final analysis designed to explore whether the size words produced in the Gesture + Talk Switch condition did the work that we have attributed to gesture, we substituted size words referring to the smallest discs for one-handed gestures in our analysis that contrasted the Gesture + Talk Switch condition with the other conditions combined. When we regressed percentage of size words referring to the smallest disc group (Gesture + Talk Switch group versus the other three Talk groups combined), and the interaction (percentage of size words × group) on change in solution time (or moves) from TOH1 to TOH2, we found no significant interaction between group and number of size words, for either change in solution time, $\beta = -60.7$, $t = -1.2$, $p = 0.22$, or change in moves to solution, $\beta = -12.1$, $t = -1.2$, $p = 0.24$. Participants' use of size words cannot account for the effect seen in Figure 5.

Discussion

Our study replicates previous work by Beilock and Goldin-Meadow (2010) and Goldin-Meadow and Beilock (2010). Adults who gestured while explaining their solution were subsequently at a disadvantage when the physical properties of the puzzle changed (Gesture + Talk Switch). In contrast, adults who gestured while explaining their solution improved their performance when the physical properties of the puzzle were not changed (Gesture + Talk No-Switch). Importantly, adults who had more experience physically moving the discs were *not* hurt by a change in the weight of the discs; these groups improved over time not only when the disc weights were not changed at TOH2 (Action No-Switch), but also when the disc weights were changed (Action Switch).

In addition, our study extends previous work by demonstrating that adults who talked while moving the discs improved their performance whether the disc weights were not changed (Action + Talk No-Switch) or changed (Action + Talk Switch) at TOH2. The change in performance from TOH1 to TOH2 for both Action + Talk groups was significantly different from the performance for the Gesture + Talk Switch group. Taken together, these findings suggest that the coordination of hand movements with speech is not the factor driving the decline in performance on TOH2 for the Gesture + Talk Switch group; this coordination was also present in the Action + Talk Switch group whose performance did not decline at TOH2.

Our data thus suggest that gesture's capacity to influence thought is not due to its tight links with language alone. We propose instead that using gesture to describe physical interactions with the environment generates strong mental representations that involve physical properties of the action and/or the environment (properties like weight). The representational nature of gesture – action in the absence of an object to be acted upon – may be particularly important for influencing thought. Speech on this task did not lead to a similar representation of weight – in fact, none of the participants in either of the Talk groups mentioned the weight of the discs in speech during the explanation phase. This omission is not surprising given that disc weight is neither relevant nor useful to finding a solution to this logic problem. However, it is worth underscoring the omission as it makes it clear that our participants did *not* encode weight in speech.

Participants also did not explicitly refer to the number of hands they used to move the discs – this information was encoded only in their actual hand movements (action or gesture). Recall that there were no significant differences across the Gesture + Talk, Action + Talk and Action conditions in the number of one-handed movements used in relation to the smallest disc during the phase of the study intervening between TOH1 and TOH2. But the one-handed movements had an impact on subsequent performance in only one group – when the movements were used representationally (Gesture + Talk) and when the information conveyed interfered with subsequent performance (Switch).

Participants in the Gesture + Talk group were asked to explain their stepwise solution in the absence of the TOH puzzle; this task required participants to create, hold in mind and update a mental representation of the apparatus itself. Gesture may aid in this task by supporting mental imagery, including not only the features of the TOH puzzle but also information about participants' physical interaction with the discs. Information about the weight (but not the size) of the discs may thus be re-enforced during the Gesture + Talk explanation. We postulate that participants in the Action and Action + Talk conditions did not construct this rich mental simulation because they could rely on the affordances of the objects themselves. When participants interact with the puzzle using concrete actions, even when task-relevant speech is coordinated with those actions, much of the sensorimotor information about the discs is off-loaded onto the environment. In contrast, gestures produced in the absence of the discs have the potential to play a more influential role in constructing a mental representation of the task. When participants gestured about the smallest disc with one hand, they re-enforced a mental representation of the disc as lightweight. In this way, gesture produced a representation that was incongruent with the discs in the Switch condition, disrupting performance.

As was just mentioned, one obvious difference between the Gesture and Action conditions was that the discs were absent when the participants gestured, but were present when they acted. Note that the absence of the discs per se cannot account for the decrement in performance in the Gesture + Talk Switch group – the discs were also absent in the Gesture + Talk No-Switch group and these participants showed no decrement in performance. However, it is possible that being forced to talk about moving the discs in their absence is what led participants to construct a mental representation that contained disc weight (although there is no particular reason to think that the absent discs would, without gesture, encourage participants to incorporate weight into their mental representation – as noted earlier, weight was never mentioned explicitly in any of the groups, but was implicitly encoded in gesture by the number of hands used). Under this alternative view, the mental representation containing weight was *reflected* in gesture, rather than *caused* by gesture. Previous work has found that participants (adults and children) asked to explain TOH with the discs present do gesture throughout their explanations (Garber & Goldin-Meadow, 2002). If we are correct that gesture leads to (as opposed to reflects) the construction of a mental representation containing weight, the gestures that adults produce in the presence of the TOH discs ought to have the same detrimental effect on TOH2 performance with switched discs as the gestures produced in the absence of the discs.[4] We are currently conducting a study to test this hypothesis in which gesturing participants are provided with visual updates of the discs they are describing. Whatever the outcome of this future study, our current study makes it clear that gesture's impact on subsequent performance in the TOH task does not stem from the fact that it is coordinated with talk – the actions participants produced in the Action + Talk condition were also coordinated with talk and those actions did not lead to a decrement in performance.

Our results have important implications for the role of gesture in learning. We know from previous work that gesturing can influence thought – it can have a positive effect on thinking and learning when gesture conveys information that is consistent with the to-be-solved problem (e.g., Goldin-Meadow et al., 2009; Ping et al., 2014) or, as we have found here, a negative effect when gesture conveys information that gets in the way of subsequent problem-solving. Our findings take this phenomenon one step further by showing that it is not the tight link between gesture and speech that makes gesture such a powerful tool for thinking and learning. The findings thus lend support to the hypothesis that gesture's power stems from its representational nature.

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Notes

1. As seen in Figure 4, the Gesture + Talk No-Switch group performance does not differ significantly from any other condition for either time or moves.
2. A leverage analysis identified two data points as outliers (one participant whose change in solution time was zero, and another whose percentage of one-handed gestures was 100). The analysis showed no significant correlation between leverage and solution time ($r = 0.072$, $p = 0.834$), indicating that the two participants with the most extreme scores did not have the greatest leverage (i.e., the most influence) on our effect.
3. Participants in both the Gesture + Talk and Action + Talk groups spent more time explaining their solutions than participants in the Action condition spent demonstrating their solutions (Action: $M = 86.06$ s, $SE = 11.96$ s).
4. Another way to address this question would be to include a 'Talk-only' condition in which participants explain their solution using speech without gesture. However, pilot testing conducted by Beilock and Goldin-Meadow (2010) indicated that when participants are asked not to gesture when explaining the TOH task, they are unable to give an adequate explanation of the task, an interesting observation in itself.

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