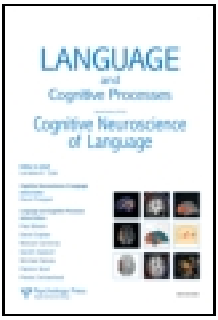

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Gestures, but not meaningless movements, lighten working memory load when explaining math

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Gestures, but not meaningless movements, lighten working memory load when explaining math

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Gesturing is ubiquitous in communication and serves an important function for listeners, who are able to glean meaningful information from the gestures they see. But gesturing also functions for speakers, whose own gestures reduce demands on their working memory. Here we ask whether gesture's beneficial effects on working memory stem from its properties as a rhythmic movement, or as a vehicle for representing meaning. We asked speakers to remember letters while explaining their solutions to math problems and producing varying types of movements. Speakers recalled significantly more letters when producing movements that coordinated with the meaning of the accompanying speech, i.e., when gesturing, than when producing meaningless movements or no movement. The beneficial effects that accrue to speakers when gesturing thus seem to stem not merely from the fact that their hands are moving, but from the fact that their hands are moving in coordination with the content of speech.

Keywords: Gesture; Working memory.

Speakers in all cultures gesture while talking. Even congenitally blind speakers who have never seen anyone gesture move their hands when they talk (Iverson & Goldin-Meadow, 1997, 1998, 2001). Moreover, the hand movements produced by blind and sighted speakers are not mindless hand waving, but rather are tightly linked to the meaning expressed in the accompanying speech. This information is accessible to listeners, who are

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able to glean specific facts from the gestures that speakers produce (Beattie & Shovelton, 1999; Cassell, McNeill, & McCullough, 1999; Goldin-Meadow & Momeni Sandhofer, 1999; Riseborough, 1981). The spontaneous gestures that accompany speech thus have a beneficial function for listeners.

But does gesture also have a function for speakers? The fact that gesture has a beneficial effect for listeners does not preclude its having a beneficial effect for speakers (see Goldin-Meadow, 2003). Indeed, gesturing has been found to benefit speakers in several ways. First, speakers talk more quickly and more fluently when gesture is permitted than when it is restricted (Graham & Heywood, 1975; Rauscher, Krauss, & Chen, 1996). Second, speakers produce fewer non-juncture filled pauses (which are associated with lexical retrieval difficulty) in speech with spatial content when gesture is permitted than when it is restricted (Krauss, 1998; Rauscher et al., 1996). Third, speakers are more likely to generate target words from definitions when gesture is permitted than when it is restricted (Frick-Horbury & Guttentag, 1998). Finally, speakers asked to explain their solutions to a math problem remember more items on an unrelated list when gesture is permitted than when it is restricted (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Ping & Goldin-Meadow, 2010; Wagner, Nusbaum, & Goldin-Meadow, 2004); gesturing can thus reduce demand on working memory (Baddeley, 1986).

However, in each of these studies designed to explore the effect of gesturing on speakers, gesturing was contrasted with not moving at all. It is therefore possible that the benefit associated with gesturing stems from its properties as a rhythmic movement synchronised with speech (cf. McNeill, 1992), rather than its properties as a vehicle for conveying meaning. In fact, moving one's hand in meaningless ways has been shown to facilitate speaking, particularly when the timing of the movement and the speech are synchronised (Chang & Hammond, 1987; Pellecchia, Shockley, & Turvey, 2005; Ravizza, 2003; Treffner & Peter, 2002; Whitall, 1996). For example, Chang and Hammond (1987) found that speech rate increased to synchronise with the rate of the speaker's cyclical finger movements. As a second example, Ravizza (2003) reported that speakers are more likely to resolve tip-of-the-tongue states when they are asked to rhythmically tap their fingers during recall than when they are asked to remain still. Thus, moving the hand in meaningless ways can improve fluency and lexical access.

The question we address here is whether moving the hand in meaningless ways can also improve working memory. Wagner et al. (2004) found that the beneficial effect of gesturing on working memory depended on the relation between the meaning expressed in gesture and the meaning expressed in the accompanying speech (see also Ping & Goldin-Meadow, 2010). When speech and gesture conveyed the same information, demand on working memory was less than when speech and gesture conveyed different information. This finding makes it clear that the coordination of information across modalities has important implications for demand on working memory. However, it leaves open the possibility that movement, even if it is meaningless, can on its own reduce demand on working memory.

We explored whether gesturing benefits working memory because it is a movement or because it is a meaningful movement by comparing experimentally elicited gestures with meaningless movements and with no movement at all. In each task, we asked speakers to remember a list of letters while explaining their answers to a math problem under three conditions: (1) speakers were told to gesture during their explanations; (2) speakers were told to produce a meaningless movement that could be easily synchronised with speech; and (3) speakers were told to hold their hands still. If the movement properties of gesture contribute to its ability to lighten a speaker's cognitive load, then speakers should perform better when asked to move than when told to keep their hands still. If the information content of gestures also contributes to its ability to lighten a speaker's cognitive load, then speakers should also perform better when gesturing than when asked to move in meaningless ways.

We decided to ask participants to gesture in this study rather than allowing them to gesture spontaneously (or not) as has been done in previous research (Goldin-Meadow et al., 2001; Wagner et al., 2004) because our design required that we ask participants to make meaningless movements. By asking participants to gesture (i.e., to move their hands in meaningful ways), we could control for possible confounding effects of instruction (i.e., elicited meaningless movements vs. spontaneous meaningful movements). Moreover, giving participants instructions ought to increase demand on working memory, making it less likely to observe a beneficial effect of gesture on working memory and thus working against our hypothesis. Finally, instructing participants to gesture has been effectively used in previous studies exploring the cognitive benefits of gesture on working memory (Ping & Goldin-Meadow, 2010).

METHODS

Participants

A total of 115 college students (62 females; mean age = 19.6 years) participated and were included in data analysis.[1] Participants were recruited using web-based sign-up and e-mail using procedures approved by the internal review board at the University of Chicago.

Procedure

Stimuli were presented using Psyscope X software (Cohen, MacWhinney, Flatt, & Provost, 1993) on a computer monitor located to the right of the participant who stood in front of a wall-mounted white board. Participants were given 30 polynomials of degree two and asked to express each polynomial as the product of two simple factors; for example, they were asked to fill in the blanks in the equation $x^2 + 5x + 6 = (\_\_\_)(\_\_\_)$ and then explain how they arrived at their answer. All of the problems could be solved using whole number factors. On each trial, participants wrote the problem on the white board and then solved it. After solving the problem, they viewed 6 consonants presented on the computer monitor for 2.5 seconds. They were then asked to hold these 6 consonants in memory while explaining how they solved the factoring problem to the experimenter who stood to the left of the participant. After completing their explanation, participants recalled the letters from memory by typing them into the computer.

Participants explained their solutions to the problems under three conditions: (1) they were instructed to gesture during their explanations (Meaningful Movement); (2) they were instructed to move both hands in circles at a comfortable rate during their explanations, a movement that could be (and was by all participants) synchronised with speech (Meaningless Movement); and (3) they were instructed to place their hands on the whiteboard tray and keep them still during their explanations (No Movement).

The instructions used in each condition were as follows: (1) Meaningful Movement: "Sometimes people explain better if they focus carefully on their explanations. One way to increase focus is to use your hands while explaining your answers. For the next 15 problems, we would like you to do this. Please be sure to use your hands while explaining your answers". (2) Meaningless Movement: "Sometimes people explain better if they focus carefully on their explanations. One way to increase focus is to move while explaining your answers. For the next 15 problems, we would like you to do this. Please move your hands in circles while explaining your answers. The experimenter will demonstrate the movement that you should perform". (3) No Movement: "Sometimes people explain better if they focus carefully on their explanations. One way to increase focus is to remain still while explaining your answers. For the next 15 problems, we would like you to do this. Please place your hands on the whiteboard tray and try to remain as still as possible while explaining your answers".

In a pilot test of the procedure, we asked each participant to produce explanations under all three conditions. However, we found that changing instructions 3 times was difficult for participants, who frequently forgot which type of explanation they were supposed to be producing. As a result, we asked each participant to produce explanations under two of the three conditions.

This design resulted in three groups: (1) a group receiving Meaningful and Meaningless Movement instructions; (2) a group receiving Meaningful and No Movement instructions; and (3) a group receiving Meaningless Movement and No Movement instructions. Order of conditions was counterbalanced within groups; problems and working memory lists were randomised across participants.

Trials where participants produced unusually short or long explanations (greater or less than 2.5 standard deviations from their own mean explanation time) were eliminated. In addition, we eliminated trials in which participants failed to solve the math problem correctly, wrote on the board during the explanation, talked to the experimenter during the explanation, dropped the pen and picked it up during the explanation, or viewed the letters prior to solving the problem. Eliminated trials accounted for 18% of the data. Including these trials in the analyses does not change the pattern of results described below.

RESULTS

Performance on the explanation task

We transcribed the gestures participants produced in the Meaningful Movement condition using a system previously developed to code gestures that participants spontaneously produce on this task (Goldin-Meadow et al., 2001; Wagner et al., 2004). Participants in our study produced sequences of points to various elements of the problem, using the index finger as well as more complex pointing hand shapes (see Figure 1 for an example), and thus produced gestures that were comparable to the gestures that participants spontaneously produced in previous studies.[2] Not surprisingly, we found that gestures were produced at a higher rate in this study than in previous studies that used an identical paradigm but without instructing participants to gesture (e.g., Wagner et al., 2004). Participants in Wagner et al. (2004) who were permitted (but not instructed) to gesture produced a mean of 6 gestures, and a maximum of 33 gestures, for each explanation on which they gestured. In contrast, when participants were instructed to gesture in the current study, they produced a mean of 13 gestures, and a maximum of 88 gestures, for each explanation.

Performance on the working memory task

We next explored performance on the working memory task. We analyzed the data using a multilevel logistic regression model to predict the likelihood of recalling each of the six letters on each trial. Multilevel modelling solves several of the problems with ANOVA (including sphericity, hierarchical

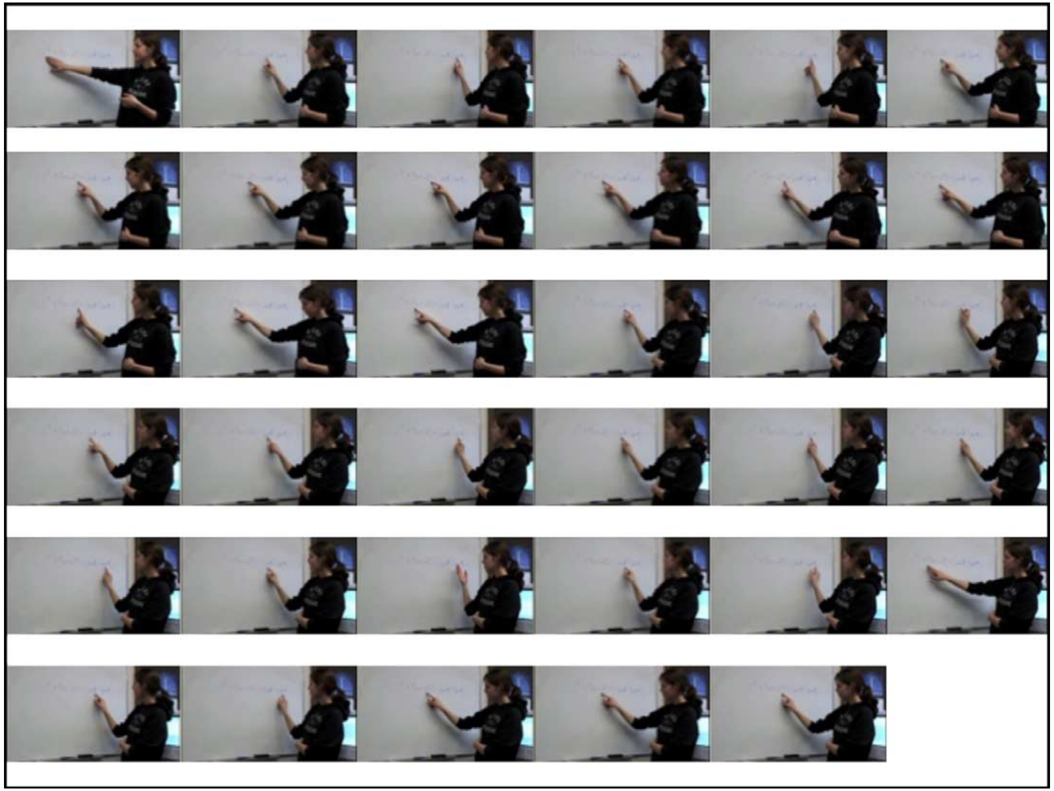

Figure 1. Example gestures from one trial with a large number of gestures during the instructed gesture condition. This participant produced 35 gestures during her explanation. [To view this figure in colour, please visit the online version of this Journal.]

sampling, and missing data) while increasing analytic power. These techniques are particularly helpful in repeated measures designs where we expect large sources of variance across individual subjects and/or items, as in the current study. It is well known that individual subjects are likely to vary greatly with respect to their working memory capacity. Using maximum likelihood estimation, we can estimate a working memory parameter for each subject, under the assumption that all participants come from a population with normally distributed working memory capacities, and then explore how experimental factors affect performance above and beyond each participants' individual working memory parameter. Similar parameters can be simultaneously estimated for each experimental item (memory list) as well as other random factors (subject, math problem, etc.), even in the face of missing, incomplete, or unbalanced data.

In our model, we included condition and trial as fixed effects, and subject, math problem, and working memory list as random effects. There was a positive effect of trial; performance improved throughout the experiment ($\beta_{\text{trial}} = .0085$, $z = 4.66$, $p < .0001$). More importantly, as can be seen in Figure 2, participants were more likely to remember the working memory items when they gestured while explaining the problem than when they produced meaningless movements ($\beta_{\text{Meaningless Movement}} = -.17$, $z = 3.23$, $p < .01$) or did not move at all ($\beta_{\text{No Movement}} = -.13$, $z = 2.61$, $p < .01$). Moreover, this effect remained even when we limited our analysis to the first

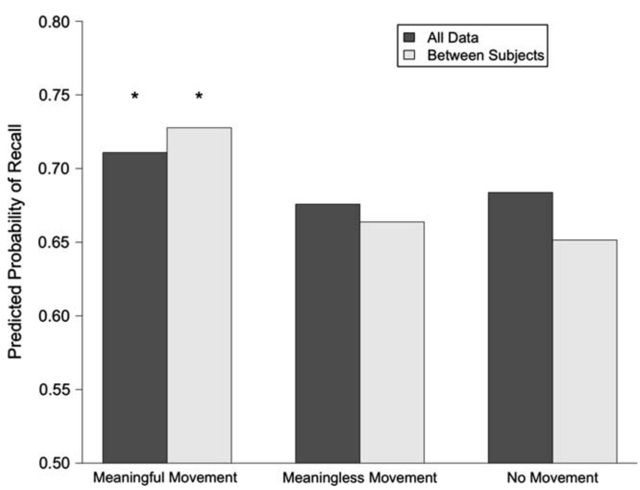

Figure 2. Probability of correctly recalling the letters in the working memory list across the experimental conditions. The within-subjects bars depict all data collected. The between-subjects bars depict performance on only the first 15 trials from each participant, with each subject contributing data to only one condition. The asterisks indicate that performance in a condition is significantly greater than performance in the other conditions.

condition each participant performed, treating the experiment as a completely between-subject design; this finding indicates that interference from prior conditions cannot account for these results ($\beta_{trial} = .026$, $z = 4.84$, $p < .0001$; $\beta_{Meaningless\ Movement} = -.30$, $z = 1.90$, $p = .057$; $\beta_{No\ Movement} = -.36$, $z = 2.30$, $p = .02$).

To explore whether gesture lightened speakers' working memory load by affecting lexical access and fluency, we transcribed and analyzed the verbal explanations produced by the two groups who participated in the Meaningful Movement condition (Meaningful Movement vs. No Movement; Meaningful Movement vs. Meaningless Movement). We examined four measures: the *number of words* in each explanation; the *speech rate* of each explanation, calculated as the number of words per second of explanation time; the *presence of non-juncture filled pauses* (all "um"s and "uh"s not occurring at clause boundaries counted as non-juncture filled pauses) in each explanation, an index of lexical retrieval difficulty (Rauscher et al., 1996; Reynolds & Paivio, 1968); and *the presence of deictic referring expressions,* defined as using the words "this", "that", and/or "these" at any point during the explanation. These words often require production of an accompanying gesture and allow for nonspecific reference in speech; in this sense, they might be relatively easy to produce.[3] For both non-juncture filled pauses and the presence of deictic referring expressions, we coded the outcome variable categorically, as present or absent, rather than continuously, because there were relatively few trials with more than one non-juncture filled pause or deictic referring expression. We analyzed the data using multilevel regression, with condition as a fixed factor, and subject, problem, and letter list as random factors. Because the degrees of freedom in linear multilevel models at present can only be approximated, we used Markov Chain Monte Carlo (MCMC) sampling to estimate the *p* values of the parameters in the linear models.

There was no reliable effect of condition for speech rate. However, there was a reliable effect of condition for the number of words used per explanation. Participants in the Meaningless Movement condition used more words than participants in the Meaningful Movement and No Movement conditions (estimated means: Meaningful Movement 46.9 vs. No Movement 46.3 vs. Meaningless Movement 52.8, $\beta_{Meaningless\ Movement} = 5.9$, $t = 3.28$, $p_{MCMC} < .01$; $\beta_{No\ Movement} = -.59$, $t = 0.46$, *ns*). There was also a reliable effect of condition for the presence of non-juncture filled pauses. Participants in the Meaningless Movement condition were less likely to produce a non-juncture filled pause (indicating facilitation in lexical access) than participants in the Meaningful Movement and No Movement conditions (estimated probability of producing a filled pause in each explanation: Meaningful Movement 0.24 vs. No Movement 0.26 vs.

Meaningless Movement 0.16, $\beta_{\text{Meaningless Movement}} = -.56$, $z = 2.62$, $p < .01$; $\beta_{\text{No Movement}} = .09$, $z = 1.12$, *ns*). Finally, there was also a reliable effect of condition for the presence of deictic referring expression. Participants in the No Movement condition were less likely to produce deictic referring expressions than participants in the other two conditions, who did not differ from one another (estimated probability of deictic reference: Meaningful Movement 0.45 vs. No Movement 0.19 vs. Meaningless Movement 0.40, $\beta_{\text{Meaningless Movement}} = -.17$, $z = 0.77$, *ns*; $\beta_{\text{No Movement}} = -1.23$, $z = 5.58$, $p < .0001$).

To explore whether these differences in verbal production could account for the difference in demand on working memory shown in Figure 1, we added all three of our reliable measures of verbal explanations into our regression analysis of working memory performance. None of the measures of participants' explanations reliably accounted for variability in recall of the letters ($\beta_{\text{word count}} = .0005$, $z = 0.32$, *ns*; $\beta_{\text{filled pauses}} = .15$, $z = 1.65$, *ns*; $\beta_{\text{deictic}} = -.10$, $z = 1.26$, *ns*). Moreover, the overall pattern of performance for the experimental conditions remained the same: participants performed significantly worse in the No Movement condition ($\beta_{\text{No Movement}} = -.13$, $z = 2.01$, $p = .044$), and marginally worse in the Meaningless Movement condition ($\beta_{\text{Meaningless Movement}} = -.25$, $z = 1.76$, $p = .079$), than participants in the Meaningful Movement condition. Thus, it seems unlikely that differences in verbal production account for the differences in working memory performance we observed.

Implementation of our instructions

Although participants in all three conditions were given instructions in what to do during the explanation phase of the study, participants in the Meaningless Movement condition were instructed to perform an atypical movement, and participants in the No Movement condition were instructed to remain atypically still. The decrement in performance on the working memory task in these two conditions relative to the Meaningful Movement condition might therefore be due to the fact that these participants had to continually remember what to do—in contrast to participants in the Meaningful Movement condition, who only had to remember to do what one typically does on this task (i.e., gesture). In order to explore this possibility, we examined performance on the memory task when speakers produced an extremely large number of gestures, that is, when speakers were clearly producing behaviours to comply with an experimental instruction rather than simply producing the same behaviours they would have produced without instruction. We reanalyzed the data, including only those trials when participants gestured more than 33 times—the top 5% of all instructed gesture trials. Even in this extremely restricted database, the pattern of performance remained the same: participants performed reliably better in the Meaningful Movement condition than in the Meaningless Movement and No Movement conditions ($\beta_{\text{Meaningless Movement}} = -.53$, $z = 2.93$, $p < .01$, $\beta_{\text{No Movement}} = -.49$, $z = 2.70$, $p < .01$).[4] Thus, even when participants were producing meaningful movements (gestures) at a rate that was clearly responsive to an experimental instruction, they showed a working memory benefit, relative to producing meaningless movements or no movements in the other two conditions. It therefore seems unlikely that the instruction to produce meaningless movements or no movements is accounting for the working memory findings presented in Figure 2.

DISCUSSION

Gesture, but not meaningless movement, lightens demand on working memory

Why do we move our hands when we speak? We might move them for our listeners––previous work has shown that our listeners do benefit from the hand gestures they see (Driskell & Radtke, 2003; Goldin-Meadow & Momeni Sandhofer, 1999; Thompson & Massaro, 1986). But we also might move them for ourselves—indeed our findings show that speakers benefit from their own gestures. Speakers in our study remembered more letters when they produced meaningful movements, that is, gestures, while explaining their solutions to a math problem than when they produced meaningless movements or no movements at all. Gesturing thus seems to lighten the speaker's working memory load and therefore serves a function for speakers as well as listeners.

Importantly, it is gesture's meaningfulness that seems to be responsible for its beneficial effects, in both listeners and speakers. Meaningful gestures produced along with a sentence facilitate *listeners'* recall of that sentence, relative to non-meaningful gestures, mismatching gestures, or no gestures at all (Feyereisen, 2006). Gesture's meaningfulness is thus important for listeners (see also Goldin-Meadow & Momeni Sandhofer, 1999; Goldin-Meadow & Singer, 2003). The work reported here extends this claim to *speakers*, demonstrating that whether or not a speaker's movements are meaningful also matters. The meaningless movements that we taught our participants were, for the most part, produced in temporal synchrony with speech. But these movements did not lighten demand on speakers' working memory (although they did appear to provide some benefit in terms of lexical access). However, producing movements that were related to the meaning of the accompanying speech—that is, gestures—did lighten demand on working memory for speakers, even when participants produced many more gestures than is typical. These findings suggest that gesture's beneficial effects on working memory stem from its properties as a movement synchronised with meaning encoded in speech.

We found no evidence that restricting movement led to decreases in participants' verbal production or increases in their difficulties with lexical access, as has previously been reported in the literature (Rauscher et al., 1996). There are several possible explanations for this difference. First, the explanations produced by participants in our study did not involve spatial language, the domain in which gesture's effects on lexical access have been reliably observed in spontaneous speech (Rauscher et al., 1996). Second, our participants were asked to explain the same type of math problem on every trial and therefore needed access to a restricted pool of lexical items for their explanations. In contrast, most studies showing that gesture plays a role in lexical access have used paradigms eliciting a variety of relatively obscure lexical items, or have focused on access failure during tip-of-the-tongue states (Frick-Horbury & Guttentag, 1998; Ravizza, 2003). Because accessing lexical items was not particularly difficult for participants in our task, there is no reason to expect gesturing (or not gesturing) to affect their ability to retrieve lexical items. If anything, participants in the Meaningless Movement condition showed a benefit on one measure of lexical access (non-juncture filled pauses) relative to Meaningful Movement and No Movement, but without a concurrent benefit on working memory performance. This finding is consistent with reports that movement can facilitate lexical access and fluency (Chang & Hammond, 1987; Pellecchia et al., 2005; Ravizza, 2003; Treffner & Peter, 2002; Whitall, 1996). Importantly, however, lexical access and verbal production were not enough to explain the working memory benefit associated with gesturing in our study, suggesting that movement may work differently to facilitate working memory than it works to support verbal production.

One way that movement has been hypothesised to facilitate speech production is by increasing activity in motor areas that are used in speech production (Ravizza, 2003). Our data are consistent with this hypothesis. On this account, movement may facilitate implementation of an articulatory code after a particular lexical item has been selected, leading to fewer non-juncture filled pauses and increasing the number of words that can be produced in a given amount of time. In contrast, gesture may facilitate selection of appropriate lexical items for subsequent production. This hypothesis is consistent with our data in that gestures did not facilitate lexical access (as measured by non-juncture filled pauses) even when we did see an effect of movement on lexical access (again as measured by non-juncture filled pauses). Note, however, that gestures are also movements and, as such, ought to have facilitated speech production and lexical access. This hypothesis thus does not explain why we did not see a general effect of gesture on lexical access.

The gestures that were produced in our study were primarily deictic gestures directed at entities visible in the environment. It is thus possible that our findings are restricted to gestures that point out objects in the immediate surround. However, recent work using a similar paradigm (although a different task, conservation of quantity) has shown that iconic gestures produced "in the air" and not anchored to objects in the room benefit working memory as do the gestures reported here (Ping & Goldin-Meadow, 2010), suggesting that the working memory benefit associated with meaningful gestures may not be limited to gestures that refer to objects in the visible world.

Gesturing lightens demand on working memory even when the speaker is told to gesture. Adults who participate in our studies are typically not consciously aware of the gestures they produce when explaining their solutions to the math problems (Goldin-Meadow et al., 2001, Wagner et al., 2004). As an example, when we debrief participants at the end of our studies and tell them that our goal is to observe their gestures, many apologise for not having gestured––even though they actually gestured on every possible problem. Interestingly, awareness of one's gestures does not seem to matter for the working memory effects observed here. Indeed, inducing gesture experimentally, and thus drawing attention to gesture, may not be as detrimental as previously assumed (cf. Goldin-Meadow & Alibali, 1994) and may even enable speakers to capitalise on properties of a representation that they would not have otherwise produced. Telling children to gesture during a lesson has, in fact, been found to make children particularly likely to learn the lesson (Broaders, Cook, Mitchell, & Goldin-Meadow, 2007; Cook, Mitchell, & Goldin-Meadow, 2007). Moreover, like the findings reported here, the meaningfulness of the movement affects the amount that is learned (Goldin-Meadow, Cook, & Mitchell, 2009). Our findings extend this phenomenon by demonstrating that gesture, be it spontaneous or experimentally elicited, not only facilitates learning but also benefits working memory processing.

How does gesture lighten the load? Potential mechanisms

The data presented here demonstrate that working memory is a locus of interaction for speech and gesture and that gesturing reduces demand on working memory. Although our data does not pinpoint a particular mechanism for this effect, they do narrow down the class of potential mechanisms to those highlighting gesture's ability to function as a vehicle for meaning. Gesture conveys meaning differently from speech and this difference may be important in gesture's ability to lessen speakers' demand on working memory. For the most part, speech conveys information categorically, relying on discrete units that are systematically combined in rule-governed fashion (but see Shintel, Nusbaum, & Okrent, 2006). In contrast, gesture conveys information imagistically, relying on an analogue rather than a discrete representational format (Goldin-Meadow & McNeill, 1999; Goldin-Meadow, McNeill, & Singleton, 1996; McNeill, 1992). Information represented in an analogue format could serve to frame, and perhaps augment, the information represented in a discrete format; the additional structure could then serve to lighten demand on working memory. For example, in the math factoring problems used in our study, the location of a number, more than its value, constrains the particular mathematical operations that must be performed on that number to solve the problem. Gesturing highlights the location of a number; speech gives its value (Table 1). Adding gesture thus frames the information encoded in speech, structuring it in a way that could benefit working memory. Consistent with this hypothesis, gestures that do *not* convey the same meaning as the speech they accompany reduce demand on working memory less than gestures conveying the same meaning (Wagner et al., 2004;

TABLE 1
Types of information conveyed in speech and in gesture in explanations of the math factoring problems

Example problem: $x^2 + 5x + 6 = (x + 3)\ (x + 2)$

Type of Information	*Speech*	*Gesture*
Adding	"3 plus 2 is 5".	Point to 3, then 2, then 5, drop hand.
Multiplying	"3 times 2 is 6".	Point to 3, then 2, then 6, drop hand.
Combining terms	"3*x* plus 2*x* is 5*x*".	Point to 3, then to the right *x*, pause, point to 2, then to the left *x*, pause, point to 5*x*.
Factoring	"I wanted factors of 6 like 1 and 6 or 2 and 3".	Point to 6, point to 6 again.
Constrained factoring	"I wanted factors of 6 that added up to 5".	Point to 6, point to 5.
x^2	"The *x* squared needs to be broken into *x* and *x*".	Point to the *x* squared, point to the left *x*, point to the right *x*.
Signs	"If the 2 signs over here are both plusses, then they both have to be plusses in the parentheses".	Point to the first plus, point to the second plus, point to the first plus in parentheses, point to the second plus in parentheses.
Multiplying signs	"The 6 has a plus in front of it so these signs are plus and plus which multiply out to another plus".	Point to the second plus, point to the first plus in parentheses, point to the second plus in parentheses.
Adding signs	"The 5 has a plus in front of it so these signs are plus and plus which add to another plus".	Point to the first plus, point to the first plus in parentheses, point to the second plus in parentheses.

but see Ping & Goldin-Meadow, 2010, for evidence that the effect may be different for novices).

Alternatively, gesture produced along with speech could work to lighten the speaker's working memory load, not by bringing an analogue format to speech, but by conveying the same information in a second modality. Indeed, maintaining information in both a spoken and a visual format in working memory has been found to place less demand on memory than maintaining information in a single format (Goolkasian & Foos, 2005). The most straightforward way to explore this possibility would be to conduct our study with signers. Although produced in the manual modality, sign languages such as American Sign Language are composed of discrete categories systematically combined in rule-governed fashion (Bellugi & Studdert-Kennedy, 1980; Klima & Bellugi, 1979). In other words, sign language is, for the most part, a discrete representational code. But signers gesture along with their signs (Emmorey, 1999), and those gestures are, almost by definition, analogue in form. If we could find a way to manipulate a signer's gestures, we could then explore whether gesturing lightens signers' working memory load. If so, we would have evidence that the beneficial effect gesturing confers on working memory stems from gesture's properties as an analogue format used in conjunction with a discrete format (be it sign or speech). If, however, gesturing while signing does *not* lighten signers' working memory load, it is likely that gesture's beneficial effect on speakers' working memory stems from the fact that gesture is produced in a different modality from speech.

Another possibility is that gesturing benefits speakers, not by directly affecting the way in which information is represented in working memory, but by helping them manage their attention. Differences in management of attention are related to differences in working memory capacity (Cowan et al., 2005; Engle, 2002). Gesturing while speaking could help speakers focus their attention on the task at hand, thereby minimising intrusions from irrelevant information and lightening the speaker's working memory load.

As a final possibility, gesturing might work to lighten a speaker's working memory load because it externalises ideas. Individuals have been found to manipulate aspects of their external worlds to ease their cognitive burden. For example, Tetris players rotate pieces on the screen to avoid rotating pieces mentally (Kirsh & Maglio, 1994), and map readers turn maps so that they are oriented in the direction of travel. Perhaps speakers use their gesturing hands to create environmental affordances that facilitate the coordination of their internal representations with the external world. Over time, as internal and external representations become coordinated, speakers may no longer rely on gesture (Chu & Kita, 2008)—thus gesture might be particularly important for lightening the load when explaining new or difficult concepts. Gesturing could also provide a way for speakers to use the external world to fill in gaps in their internal representations (Ballard, Hayhoe, Pook, & Rao, 1997), thus decreasing how much information needs to be stored. For example, pointing at particular numbers in the problem may alleviate the need to internally represent the locations of those numbers. As a result, speakers could have less complete (and therefore less burdensome) internal representations when gesturing than when not gesturing— which could lessen demand on working memory.

Gesture may be unique as an externalising technique in that the body, rather than an artifact, is the vehicle for the externalised information. Gesture could thus be a reflection of embodied cognition (cf. Beilock & Goldin-Meadow, 2010; Glenberg & Kaschak, 2002; Zwaan, Madden, Yaxley, & Aveyard, 2004; Zwaan, Stanfield, & Yaxley, 2002). Thoughts that are grounded in perceptual and motor systems may lend themselves to being gestured. Indeed, Lakoff and Nunez (2000) have proposed that mathematical concepts have been shaped by, and perhaps developed out of, the physical interaction of the body and the world. On this account, abstract mathematical concepts such as multiplication are represented as the interaction of actual entities, rather then the manipulation of symbolic referents. Consistent with this account, the gestures produced by speakers in our study sometimes depicted numbers coming together and being broken apart. Our findings suggest that using the body to externalise mathematical notions lessens the speaker's working memory load. In addition, our findings make it clear that it is not moving the body *per se* that has an impact on working memory—it's using the body as a representational vehicle (see also Goldin-Meadow & Beilock, 2010).

In sum, speakers often gesture with their hands while talking, even when they do not appear to be having difficulty with lexical access or fluency. Our findings suggest that doing so can function to lighten one's working memory load. Importantly, moving the hands in rhythmic synchrony with speech does not lighten the load on working memory. To lighten this load, speakers need to move their hands in meaningful ways.

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