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Better together: Simultaneous presentation of speech and gesture in math instruction supports generalization and retention

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ABSTRACT

When teachers gesture during instruction, children retain and generalize what they are taught (Goldin-Meadow, 2014). But why does gesture have such a powerful effect on learning? Previous research shows that children learn most from a math lesson when teachers present one problem-solving strategy in speech while simultaneously presenting a different, but complementary, strategy in gesture (Singer & Goldin-Meadow, 2005). One possibility is that gesture is powerful in this context because it presents information simultaneously with speech. Alternatively, gesture may be effective simply because it involves the body, in which case the timing of information presented in speech and gesture may be less important for learning. Here we find evidence for the importance of simultaneity: 3rd grade children retain and generalize what they learn from a math lesson better when given instruction containing simultaneous speech and gesture than when given instruction containing sequential speech and gesture. Interpreting these results in the context of theories of multimodal learning, we find that gesture capitalizes on its synchrony with speech to promote learning that lasts and can be generalized.

Gestures are hand movements, often accompanying spoken language, that are meaningful and convey information to listeners (see Goldin-Meadow, 2003; Goldin-Meadow & Brentari, 2015; Kendon, 2004; McNeill, 1992). For example, a gesture can represent the approximate size of an object, point to or reference an important part of the visual environment, or demonstrate a mimed action, such as how to rotate an object in space. Across a wide range of academic domains and age groups, students learn better from spoken instruction that includes gesture than from spoken instruction that does not include gesture (e.g., Goldin-Meadow & Singer, 2003; Macedonia, Müller, & Friederici, 2011; Ping & Goldin-Meadow, 2008; Singer & Goldin-Meadow, 2005; Valenzeno, Alibali, & Klatzky, 2003). Instruction that combines speech with gesture is particularly beneficial in helping learners generalize what they learn to new problems and retain that understanding over time (e.g., Cook, Duffy, & Fenn, 2013; Goldin-Meadow, 2014). Most research on gesture and learning to date has focused on *whether* gesture-based instruction is beneficial to learners. Here, we move beyond this question to ask *how* incorporating gesture into instruction improves learning.

The first possibility is that gesture is a powerful learning tool because it is an action performed by the hands and is thus an instance of embodied cognition (e.g., Glenberg, 2008; Niedenthal, 2007; Raymond & Gibbs, 2006; Smith, 2005; Wilson, 2002; Clark, 2007). For example, when individuals move their hands in a problem-solving scenario, they do well with respect to learning (Brooks & Goldin-Meadow, 2016), retention (Cook, Mitchell, & Goldin-Meadow, 2008), and insight (Thomas & Lleras, 2009). In these cases, gesture may be helping learners use their own bodies to create an enriched representation of a problem grounded in physical metaphors (see Alibali & Nathan, 2012; Cook et al., 2008; Hostetter & Alibali, 2008; Nathan, 2008). Importantly, learners can also learn from other peoples' gestures, perhaps because observing gesture engages the observer's motor system (e.g., Macedonia et al., 2011; Ping, Goldin-Meadow, & Beilock, 2014; Wakefield, James, & James, 2013).

But gesture's impact on learning may result not only from the fact that it is produced by the body, but also from the fact that it is produced simultaneously with speech. Gesture's ability to co-occur with speech allows instructors to convey two separate, yet complementary, messages *at the same time* (e.g., Goldin-Meadow &

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Singer, 2003; Goldin-Meadow, Cook, & Mitchell, 2009; Singer & Goldin-Meadow, 2005). Under this hypothesis, temporal synchrony between speech and gesture instruction during a learning episode is necessary to promote the best learning outcomes.

There are several pieces of evidence that provide support for this hypothesis. First, speech and gesture have been argued to share a common cognitive origin that forms an integrated system in communicative contexts (e.g., Loehr, 2007; McNeill, 1992). In natural discourse, gesture tends to be initiated just prior to speech production, and statistical analysis of naturalistic conversations reveals tight rhythmic synchrony between gesture and speech (e.g., McNeill, 1992). This tight relationship seems to be specific to gesture——speech is *more* closely synchronized with gesture than with other types of movement (e.g., action on objects, Church, Kelly, & Holcombe, 2014). And if the synchrony between speech and gesture is artificially disrupted by a mere 360 ms, overall comprehension is impaired (Habets, Kita, Shao, Özyurek, & Hagoort, 2011).

In addition, Mayer's (2005) work on multimedia learning suggests that any instruction that takes advantage of dual channels of information processed simultaneously (visual/pictorial *and* auditory/verbal) can be beneficial for learning. This and other dual-coding theories of processing are based on the assumption that humans have limited processing capacity in any single input channel, but can increase their overall cognitive processing load by taking in information in two channels at once (Baddeley, 1986, 1999; Chandler & Sweller, 1991). Importantly for the current paper, students learn most effectively when verbal and visual information are temporally and spatially integrated rather than presented separately (Mayer, 2002). This idea, known as the Contiguity Principle, has been used to suggest that learners can make more meaningful connections and better integrate verbal and pictorial input when the two are presented at the same time, as long as neither channel is subject to processing overload (Mayer & Moreno, 2003). Gesture, while not pictorial in the same way as other traditional instructional images, relies on the visual channel and thus may be effective because it can present information in a non-verbal format simultaneously with verbal information.

To date, all studies exploring the effects of instructor gesture on student learning have presented gesture simultaneously with speech and thus do not put the simultaneity hypothesis to the test. Here we directly explore whether simultaneity with speech is necessary for an instructor's gesture to have an effect on learning by manipulating the timing of an instructor's speech and gesture.

Our study design builds on the work of Singer and Goldin-Meadow (2005). In their study, all participants were given instruction containing either one or two correct strategies for solving difficult missing-addend mathematical equivalence problems (e.g., $4 + 3 + 7 = \_\_ + 7$). These types of math problems are an important precursor to algebra, and predict math fluency when controlling for IQ, race, socioeconomic status, and gender (McNeil, Fyfe, & Dunwiddie, 2015). Children in the United States as old as 4th grade have a fragile or non-existent understanding of the equals sign and consistently solve this type of problem incorrectly (e.g., Falkner, Levi, & Carpenter, 1999; Ginsburg, 1989; Saenz-Ludlow & Walgamuth, 1998). In Singer and Goldin-Meadow's most successful training condition, children were simultaneously presented with one strategy in speech and a different, but complementary, strategy in gesture. In speech, they heard the Equalizer (EQ) strategy, a principle that focuses on the idea that the two sides of an equation must be equal. In gesture, children saw a series of hand movements representing the Add-Subtract (AS) strategy, an algorithm in which all the addends on the left side of the equation are added, and then the number on the right side is subtracted from that total to get the answer. Children learned significantly more from this "mismatching" instruction containing EQ in speech and AS in gesture, compared to instruction containing these same two strategies, EQ and AS, presented entirely in speech without any gesture (and also compared to instruction containing only one of the strategies, EQ, presented in speech and gesture).

Learning a conceptual strategy (like EQ) along with a procedural strategy (like AS) in instruction leads to more flexible and generalizable learning than focusing on only one type of strategy (Baroody, 2003; Rittle-Johnson & Siegler, 1998). Gesture may be particularly good at promoting an understanding of EQ in relation to AS because the simultaneous presentation of two messages (which is not possible within the spoken modality, but often happens across speech and gesture, Goldin-Meadow, 2003) facilitates integration and comprehension of the two messages, leading to better learning outcomes than sequential presentation of the same two messages. Alternatively, gesture's ability to co-occur and be seamlessly integrated with speech may *not* heighten its power as a teaching tool. If so, presenting two complementary ideas across two modalities without integrating them temporally may be just as beneficial for learning as presenting the ideas simultaneously. In fact, sequential presentation of speech and gesture could be even more effective for learning since it might allow children time to independently focus on, and process, incoming information from each of the two modalities.

We tested these alternatives by presenting children with two complementary strategies for solving a mathematical equivalence task: EQ and AS. Following Singer and Goldin-Meadow (2005), we gave one group both strategies in speech, which were necessarily presented sequentially (S➔S), and we gave a second group the strategies across modalities, EQ in speech and AS in gesture, presented simultaneously (S✚G). To determine whether gesture's power as a teaching tool comes from its ability to be simultaneously produced with speech, we added a third group who also received EQ in speech and AS in gesture, but the two strategies were presented sequentially (S➔G). Given previous research on gesture's power to promote generalization and retention over time (Cook et al., 2013), we were specifically interested in whether the benefits of gesture would emerge (1) after a delay of either one day or one month, and (2) on generalization problems, either immediately or after a delay.

The instruction procedure was based on Singer and Goldin-Meadow (2005), but in order to ensure that the conditions were equal in terms of clarity of instruction, we made several modifications to the instruction procedure. In the original study, children in the S➔S condition heard one speech strategy on the first presentation of a problem, and then heard the second speech strategy on a second presentation of the same problem. Separating the two presentations in this way may have discouraged the children from integrating the two strategies. To avoid this potential confound, in both sequential conditions (S➔S and S➔G), we gave the two strategies within a single presentation of the math problem, with no break in between the two strategies, just as we did in the simultaneous condition (S✚G). Singer and Goldin-Meadow (2005) found a difference in learning between the two groups in their study, our S✚G and S➔S groups, immediately after instruction. Because we were primarily interested in the impact of gesture on generalization and retention, and because we were concerned that presenting speech and gesture sequentially (S➔G) might be off-putting (since it is an unusual way to present the strategies), we decided to try to increase initial learning across the groups by providing experimenter feedback on all problems. We reasoned that if children in all conditions were to perform similarly on the problems solved immediately after the lesson, we could then be confident that children can learn from an unusual lesson (i.e., from S➔G) and that any subsequent differences found across the groups in their performance on generalization problems or retention over a delay do

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