Analogical gestures foster understanding of causal systems

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Abstract

Sensitivity to the causal structure underlying phenomena is critical to expert understanding. Fostering such understanding in learners is therefore a key goal in education. We hypothesized that observing *analogical gestures*—which represent relational information in visuospatial format—would lead learners to notice and reason about underlying causal patterns, such as positive and negative feedback. Participants watched brief video lectures about the human body and the plant kingdom, which were delivered along with gestures representing either: 1) visuospatial details (*iconic gesture condition*); or 2) relational structure (*analogical gesture condition*). In a subsequent classification task, relative to participants who saw iconic gestures, participants who saw analogical gestures were more likely to sort the phenomena described in the videos—as well as novel phenomena—by their causal structure (e.g., positive feedback). The results suggest that analogical gestures can be harnessed to foster causal understanding.

Keywords: analogy; relational reasoning; gesture; learning; complex systems

Introduction

A deep understanding of any complex phenomenon—from the ebb and flow of the tides, to the rise and fall of blood pressure—requires an understanding of the causal structure that gives rise to it (Lagnado, Waldmann, Hagmayer, & Sloman, 2007; Mackie, 1980; Sloman, 2005). Yet this is no trivial task. The causal relations that govern phenomena throughout the physical and social world are often embedded in a wealth of concrete, causally irrelevant particulars (e.g., Rottman, Gentner, & Goldwater, 2012). Thus a key question for cognitive scientists and educators alike is: How do people come to understand causal structure, and how can we foster this understanding?

We focus here on an important arena of causal understanding: namely, *causal systems*—abstract patterns of causation, such as positive and negative feedback, that occur in a wide range of phenomena (Fernbach & Sloman, 2009; Rottman, Gentner, & Goldwater, 2012; see also Day, Motz, & Goldstone, 2015). Feedback systems can be found in the human body, in household appliances, in economic markets, and in plant physiology, to name just a few domains. For example, in a simple two-factor positive feedback system, an increase in one causal factor causes an increase in a second factor, which in turn causes an increase in the first factor; in a negative feedback system, an increase in one causal factor causes an increase in a second factor, which then causes a *decrease* in the first factor. The challenge such systems present for a learner are considerable: To notice, for instance, the abstract causal likeness between human perspiration and a flush toilet—i.e., that both involve negative feedback—one has to look past a host of visuospatial and sensory differences between the two. One way that expertise in noticing such causal patterns comes about is through repeated opportunities to compare examples across domains, as happens over an extended science education (Rottman et al., 2012). Indeed, such a process can be induced in the laboratory by having learners analogically compare disparate examples of causal systems (Goldwater & Gentner, 2015), much as comparison can promote relational learning more generally (Christie & Gentner, 2010; Doumas & Hummel, 2013; Gentner, Loewenstein, Thomspson, & Forbus, 2009; Gick & Holyoak, 1983; Jung & Hummel, 2011; Kotovsky & Gentner, 1996; Kurtz, Boukrina, & Gentner, 2013).

Here we explore a less-studied route through which it may be possible to foster causal understanding: *analogical gestures*. In previous work, we found that, people produce gestures in abundance when explaining feedback systems (Cooperrider, Gentner, & Goldin-Meadow, 2016). These gestures were analogical in that they used space, not to represent concrete spatial details, but to represent relational structure: they used locations to distinguish causal factors, motion to show increases and decreases to those factors and causal relationships between them, and complex movements to summarize the overall relational structure of the systems. Strikingly, these gestures occurred in abundance even though participants were explaining systems that were not inherently spatial and were, by design, devoid of the kinds of concrete details that usually prompt gestures. These laboratory findings provide insights into how people express spatial analogies in gesture, and also raise an important further question: Might using such analogical gestures during instruction foster understanding of causal patterns?

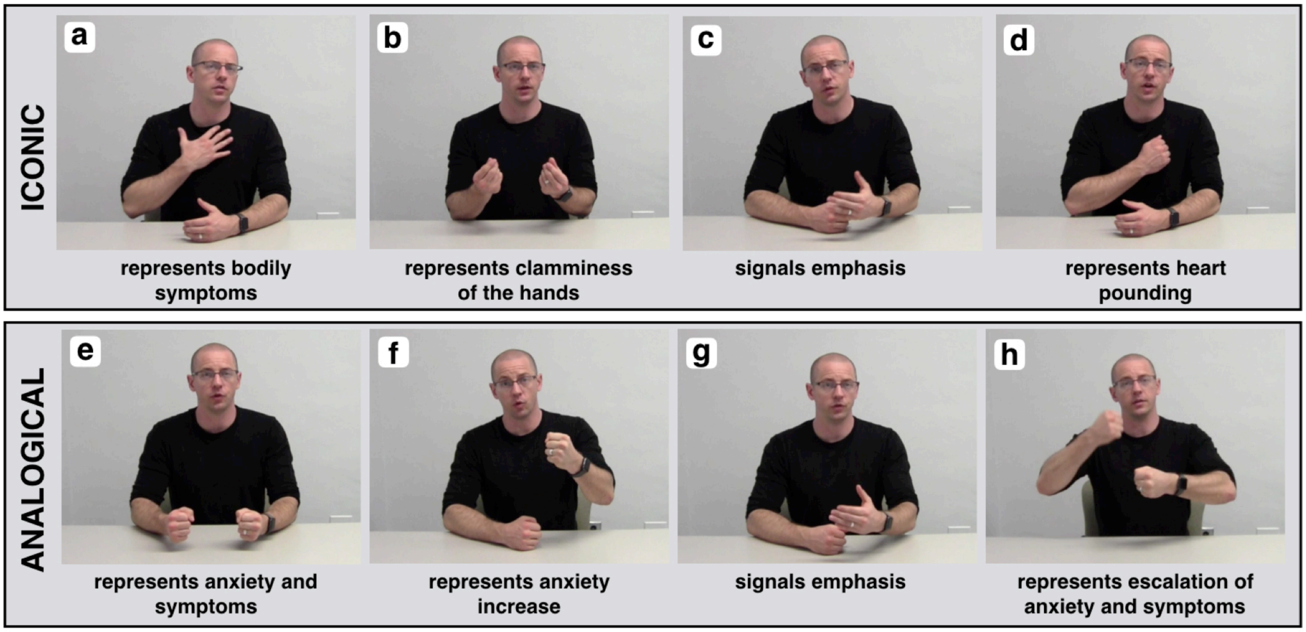

Figure 1: A selection of gestures from one of the video explanations, describing the phenomenon of anxiety attacks. In the version seen by participants in the iconic condition, all the gestures represented concrete aspects of the phenomenon (panels a, b, and d); in the version seen in the analogical condition, the gestures represented the two causal factors (e) and the pattern of increase and decrease to those factors (f and h). For all phenomena, the contrasting versions of the explanations used the same number of gestures, included beat gestures in the same places (c and g), and used an identical audio track.

Gesture is ubiquitous in everyday conversation as well as in the classroom (Goldin-Meadow, 2003). Despite being more implicit than speech (McNeill, 1992), gesture is an important medium for communicating ideas (Hostetter, 2011), including abstract ideas about relational structure (Jamalian & Tversky, 2012). Moreover, gesture has been found to boost learning in a range of content domains (Ping & Goldin-Meadow, 2008; Singer & Goldin-Meadow, 2005; Valenzeno, Alibali, & Klatzky, 2003). While prior studies have focused on gesture's consequences for young learners, gestures conveying abstract concepts have also been attested in lectures to older students, in disciplines ranging from literary studies to mathematics (Corts, 2006; Mittelberg, 2008; Núñez, 2008).

Importantly, the gestures used in everyday communication and the classroom come in different varieties, and may not all be equally effective in conveying ideas about causal structure. A first type is *iconic gestures*. These are produced in the course of explaining concrete, visuospatially rich content, and are used to represent size and shape, location, motion, and spatial relationships (Alibali, 2005; Alibali & Hostetter, 2008; McNeill, 1992). A second type of gesture is more abstract, using location, motion, and spatial relationships to represent ideas and relationships that are not inherently spatial. Such gestures include those described in our prior work on explanations of feedback systems (Cooperrider, et al., 2016), and also a range of other content domains (Cienki & Muller, 2008; Cooperrider & Goldin-Meadow, 2017; Goldin-Meadow, 2003). It is this latter type—*analogical gestures*—that we predict would lead observers to notice and reason about causal structure. Iconic gestures, by contrast, may have no effect on causal understanding, or may even hinder it by highlighting concrete particulars.

In the present study, we test the idea that analogical gestures can be used to foster understanding of causal systems—patterns which are often buried beneath concrete particulars. To this end, we created two sets of short video lectures: one in which an actor accompanies his explanations of phenomena in the human body and plant kingdom with iconic gestures that depict concrete visuospatial details (*iconic gesture condition*); another in which the actor accompanies his explanations with analogical gestures depicting relational structure (*analogical gesture condition*). We hypothesized that participants in the analogical gesture condition would be more likely to notice the underlying causal structure of the phenomena described in the lectures and, moreover, that these participants would be more likely to discern causal structure when encountering novel phenomena.

Methods

Participants

60 undergraduate students from Northwestern University participated in exchange for course credit. 15 participants were eliminated for failing a video comprehension check (described below), and two were eliminated for admitting during debriefing that they listened to the audio but did not watch the screen. In all, 43 participants (21 iconic condition,

22 analogical condition; 24 men; *M* age = 18.7 years) were included in the analyses.

Materials and procedure

Video Stimuli Drawing on materials from prior studies (Rottman et al., 2012; Smith & Gentner, 2014), we developed short descriptions of four phenomena: anxiety attacks (a positive feedback system within the domain of the human body); blood pressure regulation (negative feedback, human body); bracken fern growth (positive feedback, plant kingdom); and prayer plant cycles (negative feedback, plant kingdom). The descriptions balanced concrete details (e.g., for the anxiety attacks description: the "heart feeling like it is pounding") with clues to causal structure ("this will lead to even more intense symptoms"). We filmed an actor delivering each of these (~45 sec) explanations in two versions: one with iconic gestures depicting concrete aspects of the phenomenon described, and one with analogical gestures representing the causal factors involved in the phenomenon and the behavior of those factors (Fig. 1). The iconic gestures were based on the actor's intuitions about what would be most natural; the analogical gestures were inspired by the gestures produced spontaneously by participants when describing highly abstract versions of feedback systems (Cooperrider et al., 2016). For each phenomenon, the two versions had the same number of target—i.e., iconic or analogical—gestures (5-7 per explanation), as well as the same number of beat gestures (2-3), which were included to make the explanation more naturalistic. Finally, to control for differences in prosody, the audio track of the actor speaking was identical in the two versions. This was achieved by: 1) recording a primary audio track, 2) filming the actor talk and gesture in sync with the primary track while it played, 3) aligning the video with the primary track and removing the secondary audio.

Classification Task We developed a phenomenon classification task inspired by the Ambiguous Sorting Task (AST) used in prior studies (Rottman et al., 2012; Goldwater & Gentner, 2015). Participants were first presented with written descriptions of three new phenomena: blood clots (positive feedback, human body); spotted knapweed growth (negative feedback, plant kingdom); and internet routers (common cause, technology). These three phenomena served as the "seed" categories into which further descriptions would have to be classified. The central feature of the task, as with the AST variants used previously, is that nature of the categories is up to the participant to decide: the seed phenomena represent three different domains as well as three different causal structures, thus affording both kinds of classification.

After reviewing the seed phenomena, the participant classified eight further written descriptions, one at a time. Four of these were descriptions of novel phenomena; the other four were written versions of the videos watched earlier. Note that only six of the phenomena were "critical" in that classifying by domain and by causal structure were mutually exclusive: all four novel phenomena and two of the familiar ones (blood pressure, bracken fern). The other two familiar phenomena (anxiety, prayer plants) shared the same combination of domain and causal structure as the seed phenomena (e.g., anxiety attacks and blood clotting are both in the domain of the human body and both positive feedback systems).

Other Assessments Participants completed two further assessments of causal system understanding: a battery of inference questions and a diagram task. Both concerned only the four phenomena familiar from the videos. For the inference battery, participants answered eight questions (two per phenomenon) querying general behaviors of—and predictions about—the systems described. For the diagram task, participants were shown contrasting diagrams of positive and negative feedback, with a detailed explanation of the symbols used (e.g., plus and minus signs). Participants were then asked to match each of the videos seen previously to the correct diagram.

Procedure All video stimuli and assessments were implemented in Qualtrics and displayed on a desktop computer. The experiment started with a brief video introduction by the lecturer, which was the same for both conditions. Participants then watched the four videos in a fixed order, in the versions corresponding to their condition assignment, i.e., for a participant in the iconic condition, the iconic gesture versions of all four explanations. After watching each video, participants answered two multiple-choice questions about their basic content (e.g., which symptoms of anxiety were mentioned). These questions were intended as an attention check, and participants who got one or more wrong were excluded.

After the final video, participants proceeded to the classification task. The seed phenomena were presented as fixed blocks of text on the screen; the to-be-classified phenomena were presented, one at a time, on moveable digital "cards." Participants were instructed to: "Decide which of the descriptions [i.e., the seed phenomena] the card [i.e., the to-be-classified phenomenon] is most similar to, and drag it to that pile." The eight phenomena were presented in a fixed order, with the four novel ones first, followed by the four familiar ones. We had participants sort the novel phenomena first to encourage them to think deeply about the task, rather than sort by first impulse. After the classification task, participants completed the inference question battery and the diagram task, both in a fixed order, and were debriefed. In all, the task took around 20 minutes.

Results

Classification Task

Our primary measure was the mean proportion of phenomena that participants classified by *domain* (human body, plant kingdom, or technology), by *causal structure* (positive feedback, negative feedback, or common cause),

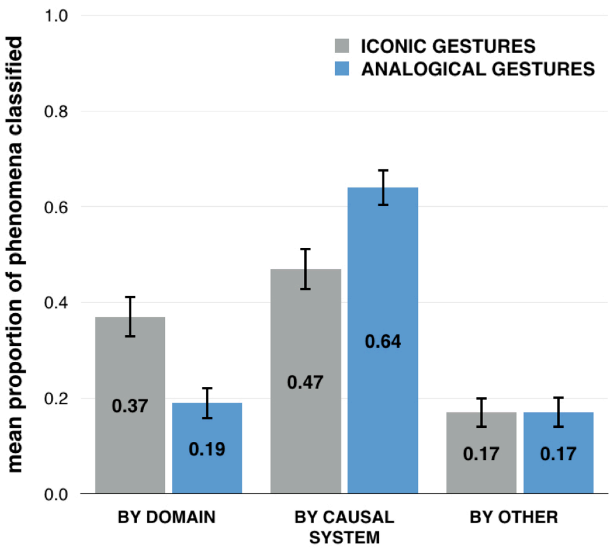

Figure 2: The mean proportion of critical phenomena classified by domain, by causal structure, or by other criteria in the two gesture conditions. Error bars represent standard error of the mean.

or by *other* criteria. We first considered only the six critical items—that is, those for which classification by domain or by causal structure were mutually exclusive. Participants in the iconic gesture condition classified a higher proportion of the critical phenomena by domain than did participants in the analogical gesture condition (iconic: M = .37, SD = .20; analogical: M = .19, SD = .16; t = -3.2, df = 41, p = .003, Cohen's d = -0.98). Conversely, participants in the analogical gesture condition classified a higher proportion of the critical phenomena by causal structure than did participants in the iconic gesture condition (analogical: M = .64, SD = .18; iconic: M = .47, SD = .20; t = 3.02, df = 41, p = .004, Cohen's d = 0.92) (Fig. 2). Participants in the two conditions sorted by some *other* criterion to the same extent (iconic: M = .17, SD = .15; analogical: M = .17, SD = .15; t < .001, df = 41, p = 1). Importantly, the same pattern of significance holds when looking only at the four novel phenomena (by domain: p = .01; by causal structure: p = .01; by other: p = .88). Indeed, for all eight phenomena, a higher proportion of participants in the analogical gesture condition sorted by causal structure than did participants in the iconic gesture condition.

To get a better sense of individual participants' classification behavior, we also zoomed in on the two critical phenomena that were featured in the videos: blood pressure regulation and bracken fern growth. Note, again, that to classify these by causal structure, participants had to resist the temptation to group the blood pressure description with the human body seed (blood clots) and the bracken fern description with the plant kingdom seed (spotted knapweed). Yet not a single participant in the analogical gesture condition classified both these phenomena by domain, compared to six participants in the iconic gesture condition who did (two-tailed Fisher's exact, p = .009)

Other assessments

Inference Question Battery Participants in both conditions answered the majority of inference questions correctly and at close to ceiling, with no difference between the conditions (iconic: M = .90, SD = .12; analogical: M = .86, SD = .13, t = -1.09, df = 41, p = .28).

Diagram Task Participants in both conditions answered the majority of diagram questions correctly and at close to ceiling, but with those in the analogical gesture condition performing marginally better (iconic: M = .80, SD = .19; analogical: M = .89, SD = .13, t = 1.82, df = 41, p = .08).

Discussion

The present study investigated the hypothesis that seeing certain types of gestures would lead observers to notice and understand causal structure. Specifically, we expected that *analogical gestures*, which represent relational structure spatially, would foster understanding of causal structure better than would iconic gestures, which represent concrete visuospatial details. This hypothesis was borne out. Participants in the analogical gesture condition noticed the causal structure of the phenomena described in videos, and were also more likely to notice causal structure in entirely new phenomena. Given the design of our classification task, this was no easy feat. To classify by causal structure, participants had to look past compelling differences of content to find deeper similarities, or look past compelling content similarities to discern deeper differences. Our prior work showed that people spontaneously produce analogical gestures when explaining causal systems; the current study builds on these findings to show that such analogical gestures have important consequences for learning.

Our leading interpretation of the present findings, again, is that observing analogical gestures led participants to notice and reason about causal structure. A second—and not mutually exclusive—possibility is that the concrete gestures in the iconic condition hindered participants from the discerning the underlying relational structure by lavishing them with vivid details. Follow-up studies with a "no gesture" control condition would clarify whether our two gesture conditions are indeed pulling observers in opposite directions or, if not, which gesture type is driving the observed pattern of results. This question is of clear theoretical interest, but we also note that, in teaching contexts, gesture is ubiquitous, perhaps even inevitable. Thus, from a practical perspective, the important question is not *whether* teachers should gesture about the phenomena they are explaining, but *how*. Our results suggest that iconic gestures, as natural as they are, may not always be the best choice. It may be that the best instructors already intuit this, using gestures that highlight relational structure when possible.

By what specific mechanism(s) did analogical gestures have their beneficial effects? We hypothesize that these gestures helped convey the causal content of each phenomenon by capturing it in schematic spatial form.

Indeed, space is a familiar and intuitive format in which to represent and reason about relational structure (e.g., Gattis, 2004; Tversky, 2011). But we think there may have also been another important reason for the efficacy of analogical gestures: namely, that they invited comparison and uniform representation across the scenarios. Participants in the analogical gesture condition viewed four videos, all featuring qualitatively similar gestures. For example, all four parsed the phenomena into causal factors by establishing locations in space, and all showed the increases and decreases to those factors as vertical movements. The gestures in the iconic gesture condition also had some commonalities across videos (e.g., the gestures in both human body videos indexed body parts), but they were hardly as schematic and alignable. Prior work has shown that using the same words in superficially different contexts prompts observers to compare those contexts (Clement, Mawby, & Giles, 1994; Gentner, 2003), and using similar gestures across different examples may have similar effects. The idea that such a mechanism drives the current results is consistent with earlier findings that prompting people to compare examples of feedback systems fosters causal understanding (Goldwater & Gentner, 2015). Thus, while we refer to the abstract gestures in the present study as "analogical" because they rely on a structured mapping between spatial structure and relational structure (Cooperrider et al., 2016), they are also "analogical" in another sense: they invite observers to form analogies across the different contexts in which they are used. Future studies might assess these mechanisms by comparing a condition in which the analogical gestures are qualitatively similar and thus alignable across lessons—as in the present study—with a condition in which the analogical gestures are more heterogeneous and thus less alignable.

What makes the present findings perhaps surprising is that co-speech gestures are largely implicit (Goldin-Meadow, 2003; McNeill, 1992). People seem to produce gestures spontaneously and unreflectively, and do not always notice the ones that others produce. Indeed, when we queried participants at the end of the present experiment about what they thought of the lecturer's gestures, several participants demurred, saying that they "didn't notice them." And yet, despite this "under the radar" quality, these gestures have clear consequences for learning (for a recent review, see Novack & Goldin-Meadow, 2015). Another question for further research is whether the implicit nature of gesture is key to its benefits. Would the techniques that speakers use to make gesture more salient—e.g., looking at their own gestures (Cooperrider, 2017)—make gesture even more powerful in instruction? And would more explicit forms of visuospatial communication, such as diagrams (Novick, 2003; Tversky, 2011) or sketches (Forbus, Usher, Lovett, & Wetzel, 2011), also be effective in fostering causal understanding?

Conclusion

Sensitivity to causal structure is a hallmark of expert understanding. Discovering how to foster such sensitivity is an important goal for cognitive scientists and educators across the natural and social sciences. Our results suggest that a ubiquitous dimension of communication—*gesture*—might be harnessed to this end. Analogical gestures like those in the present study have been elicited in the lab (Cooperrider et al., 2016), but their importance in instruction has not been investigated. The present findings offer first steps toward figuring out whether those gestures have consequences for learners and, if so, why.

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