Analysis of Touchscreen Interactive Gestures During Embodied Cognition in Collaborative Tabletop Science Learning Experiences

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Abstract: Previous work has used embodied cognition as a theoretical framework to inform the design of large touchscreen interfaces for learning. We seek to understand how specific gestural interactions may be tied to particular instances of learning supported by embodiment. To help us investigate this question, we built a tabletop prototype that facilitates collaborative science learning from data visualizations and used this prototype as a testbed in a laboratory study with 11 family groups. We present an analysis of the types of gestural interactions that accompanied embodied cognition (as revealed by users' language) while learners interacted with our prototype. Our preliminary findings indicate a positive role of *cooperative (multi-user)* gestures in supporting scientific discussion and collaborative meaning-making during embodied cognition. Our next steps are to continue our analysis to identify additional touchscreen interaction design guidelines for learning technologies, so that designers can capitalize on the affordances of embodied cognition in these contexts.

Introduction

Large touchscreen interfaces like multi-touch tabletops have become increasingly widespread, particularly in informal learning environments such as science museums (Geller, 2006). For example, science educators and researchers are using large touchscreen interfaces to support learning about complex global phenomena such as Earth's ocean system (Cheek, 2010). Yet, many visitors have trouble understanding the information presented on these interfaces, let alone interacting with the interfaces to develop a deeper understanding of the information (Cheek, 2010). Previous interaction design research has used *embodied cognition* as an underlying theoretical framework to inform the design of large touchscreen interfaces for learning (Lin et al., 2016; Piper et al., 2012). Embodied cognition theory posits that cognition is not solely based in the mind, but also in the body, i.e., some of our cognitive processes occur through "perceptually-guided motions" (Wilson & Golonka, 2013). Learning around a shared interactive display like a touchscreen tabletop with direct-touch gestures draws on the affordances of embodiment. These interactive gestures play an important role in how learners explain abstract ideas and promote scientific discussion (Piper et al., 2012). Although embodiment theories consider sensorimotor activities like direct-touch gestures to be integral to learning, the community has noted that there is still no "conceptually coherent and empirically validated design framework" to inform the design of embodied learning experiences (Abrahamson et al., 2018, p.1243). Prior research that has explored the design of touchscreen interfaces for learning from the viewpoint of embodied cognition has assumed that embodied cognition is driving learning during any motion or interaction, without considering how *specific* interactions may influence particular instances of learning. If we could identify the types of touchscreen interactions being used when people are engaged in embodied cognition during a learning episode, we could design learning experiences that explicitly support and encourage touchscreen interactions directly linked to learning.

In this paper, we analyze touchscreen gestural interactions that accompany linguistic cues of embodied cognition during collaborative learning (Kirschner et al., 2018), in the context of science learning about data visualizations of Earth's global ocean system. We built a tabletop application prototype to support collaborative learning and used this prototype as a testbed in a lab study with 11 family groups. Throughout this paper, we use the term "learning" to reflect *meaning-making*, that is, the process of integrating new knowledge and coordinating it with existing beliefs and knowledge (Vygotsky, 1978), rather than its traditional use to reflect "knowledge acquisition." Based on previous research that has shown conceptual metaphors are a type of embodiment language (Lakoff & Johnson, 2003), we relied on identifying the three main conceptual metaphors (*metonymy*, *orientation*, and *ontology)* in groups' utterances as cues to the occurrence of embodied cognition. We then analyzed participants' gestures that co-occurred with these utterances and linked these gestures to how people were making meaning at that moment. Specifically, we investigated the following research questions: (RQ1) When groups' utterances reveal that embodied cognition is occurring, what gestures are they making, during learning with an interactive tabletop? (RQ2) How can we support and encourage these types of gestural interactions in the design of computer-supported collaborative learning experiences on an interactive tabletop, to afford embodied cognition more directly? Our preliminary findings indicate a positive role of *cooperative (multi-user)* touchscreen gestures in supporting collaborative learning on tabletops during embodied cognition. This paper outlines two initial themes and touchscreen interaction design guidelines for affording embodied cognition, to inform the design of future tabletop experiences for science learning.

Embodied cognition in designing tabletop applications for learning

Prior work investigating collaborative learning around multi-touch tabletops has already used embodied cognition as a theoretical framework to design these learning experiences (Lin et al., 2016; Piper et al., 2012). Embodied cognition provides an ideal framework for understanding interactions with multi-touch technology because it considers direct hands-on interactions with the digital content to be integral to cognition (Kirsh, 2013). Lin et al. (2016) used embodied cognition as their theoretical basis to design a tabletop application to promote collaborative thinking among high school students. Their findings show that externalizing learners' thinking by adding scaffolding such as sticky notes made it easier for groups to share and reflect on their thoughts collaboratively. They note that being able to enlarge or zoom sticky notes facilitated joint reading and group thinking, implying that touchscreen gestures and collaborative thinking are intertwined. Piper and Hollan (2009) compared affordances of tabletops and pen-paper material for supporting scientific discussions with undergraduate students and noted that tabletops better supported understanding of abstract science concepts, such as how a neuron fires. Learners used bimanual and collaborative whole-handed gestures over various parts of the axon during scientific discourse. On the other side, prior work has also explored how to design direct-touch interaction generally to support science learning activities around tabletops (Horn et al., 2009; Shaer et al., 2011), although not explicitly from the standpoint of embodied cognition. Horn et al. (2009) developed an information visualization tool (*Involv*) for exploring the Encyclopedia of Life to help groups of adults effectively interact with large datasets on the tabletop. Shaer et al. (2011) explored tabletop interactions for classroom science learning and found that multi-touch tabletops encourage reflection and foster collaboration. However, these studies focus more broadly on the role of interaction in supporting science learning, rather than looking at *specific* interactions that augment scientific discussion and collaborative learning. Our work builds upon both of these lines of prior work. In addition to using embodied cognition as our conceptual framework, we analyze the gestures that are co-occurring with instances of embodied cognition (as signaled by the users' language) to understand the role of gestures in facilitating the collaborative science learning process.

Language as demonstration of embodied cognition

The theory of embodied cognition posits that learning occurs not only within the mind, but also in the body, through the learner's movements and interactions with the environment (Wilson & Golonka, 2013). Lakoff and Johnson (2003) discussed language as one signal of embodiment, specifically the use of "conceptual metaphors" for space and place, outlining three types (Table 1). *Orientational metaphors* use spatial words for ideas that are not inherently spatial. *Ontological metaphors* allow an abstract idea, such as an experience, to represent a concrete substance like an object. A specific example is *personification*: giving objects human-like qualities so we can relate experiences through human characteristics. *Metonymy* is when one idea stands in for another similar idea, as when someone speaks about a location they are not physically in as "here". Wilson and Golonka (2013) have critiqued some embodied cognition research, however, suggesting that linguistic expression of metaphors found in much embodied cognition research (including this paper) is at best a precursor to true embodied cognition, as language still occurs in the mind. The tasks investigated so far that Wilson and Golonka

Table 1: Examples of the three types of conceptual metaphors from Lakoff and Johnson (2003).

Conceptual Metaphors	**Examples**
Orientational	When we use "up" to describe feeling happy, e.g., "I'm feeling *up*." (p.16)
Ontology	When a physical object is described as "talking" or "giving" as if it were a person, e.g., "His religion *tells* him that he cannot drink fine French wines." (p.28)
Metonymy	When we use the name of one location to describe our experience associated with the events at that physical location, such as using the term "Grand Central Station" to mean "a crowded place," e.g., "It's been *Grand Central Station* here all day." (p.32)

suggest represent “true” embodied cognition tasks, such as catching a fly baseball, are considerably less “representation hungry” than our more abstract task of learning from data visualizations. Our task deals with thinking about data that is not concretely present in the learner’s environment (Kiverstein & Rietveld, 2018). For examine, one part of our task is understanding what the colors in the data visualizations depict, another part is determining the pattern(s) of the colors, and a third part is ascribing meaning to the patterns. Decomposing our meaning-making task into elements that engage embodied cognition as Wilson and Golonka do is a question outside the scope of this paper. The specific conceptual metaphors learners use are likely to be influenced by the specific science domain; however, our focus is not to categorize the types of conceptual metaphors used by learners in this domain. Instead, we focus on linking the touchscreen gestures during embodied cognition to the learning that is occurring. These insights will inform the design of future touch-interactive learning experiences to more successfully capitalize on the affordances of embodied cognition in data visualization tasks.

Our prototype application for learning about Earth’s ocean system

To study our research questions, our team, which consisted of both human-computer interaction experts and learning scientists, designed a touch-interactive tabletop prototype for science data visualizations to engage family groups in collaborative meaning-making. The application ran on a Samsung SUR40 tabletop computer. The resolution was 1920 x 1080 (55 DPI), and the display size was 40 inches, measured diagonally. We created the interface with the Open Exhibits Software Development Kit (SDK) (1).

To aid groups in the collaborative meaning-making process, we provided scaffolding (Stofer, 2016), e.g., cognitive affordances that can help non-expert users understand the ocean temperature data visualizations better, such as audience-appropriate color schemes and geographic labels. We used two map views with color scaffolding designed by NASA (2). The visualizations we used are similar to the NASA Earth Observations visualizations, which have been deployed in nearly 100 museums worldwide (3). Our prototype consisted of two “maskviewer” interface elements, each containing a set of ocean data visualizations from the year 2015 on top of a base Earth map with land maps and blue oceans (4) (Figure 1). The first visualization used a pink-to-purple color scale that showed baseline ocean temperatures, and the second visualization used a red-to-blue color scale to represent the extremes of the temperature difference (e.g., anomaly) from baseline (Stofer, 2016). The maskviewers implemented “layers” of information which could be zoomed, rotated, or dragged to allow users to flexibly control them and facilitate shared communication. To help participants recognize the difference between the two maskviewers, we attached a temperature legend and title directly to the maskviewers. Each visualization contained six continent hotspots that, when tapped, would pop-up an information box with content about El Niño, an ocean phenomenon affected by temperature, which could then be zoomed, rotated, or dragged in relation to that continent. We chose the content for these information boxes from international weather and climate organizations (5) to supplement the content shown on the data visualizations. Finally, to enable participants to explore how baseline temperatures or temperature anomalies changed over a year, our prototype contained a “time slider” (yellow bar in Figure 1). When the user performed a hold (long tap) anywhere on the map, the time slider would pop up, and the user could slide their finger horizontally along it to change the months and observe the continuous temperature changes. The time slider had tick marks for each month, labels at either end of the slider, and the current month displayed above the user’s finger. We used this prototype as a testbed to identify interactive touchscreen gestures that co-occurred with instances of embodied cognition while groups engaged in a scientific discussion about ocean temperatures.

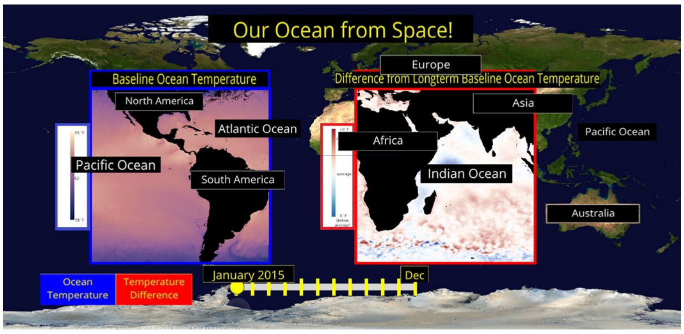


Figure 1. Prototype design with the red/blue maskviewers on a base Earth map, along with a time slider (yellow bar) to change months. Text labels have been enlarged for legibility.

Participants and study design

A total of 30 participants in 11 family groups participated in our study (16 female). Each group consisted of at least one child (ages 8 to 13, M: 10.07 yrs, SD: 1.49 yrs, 15 children total) and one parent or guardian (max group size: four). We recruited participants via an email sent to a faculty list and flyers distributed at a local science museum. Our protocol was approved by our Institutional Review Board. After obtaining informed consent and assent, we instructed groups in how to use the think-aloud process (Greenberg et al., 2011) to expose what they were thinking while completing the learning activity. We also did a practice think-aloud with them as a group to solve a two-column addition problem. During the study, we asked each group to perform these four tasks in order, while thinking aloud: (1) Explore this interactive visualization as you would if you saw it in a science museum. We are interested in seeing what people do. Tell us what you find out about the ocean. (2) Open the information box for South America and tell us how the information there compares to the ocean data displayed in general. (3) Find the Gulf of Mexico and tell us how ocean temperatures there change month to month. (4) Find the Eastern Pacific Ocean basin and tell us how ocean temperatures in the basin compare to long-term baseline ocean temperatures for that basin.

The order of tasks increased in difficulty, with the aim that, as participants explored the prototype, they would be better able to answer the more involved questions. After the tasks, participants completed a demographics questionnaire. Most of our participants (over 85%) were frequent science museum visitors (e.g., three to twelve times per year). Each family group received a $30 grocery store gift card for participating.

Data collection and analysis

During the study, we video recorded participants using cameras placed at a side angle and directly overhead. Session lengths (excluding break time between tasks) ranged from 14 minutes (min) 30 seconds (sec) to 27 min 45 sec (average duration: 21 min 43 sec, just under 6 min per task). We transcribed the groups' utterances from the videos. One group spoke some Spanish during their interaction, and we asked a colleague to assist with translation. To understand how specific interactions may be tied to particular instances of learning supported by embodiment, we first identified the set of learning "episodes" in which groups' utterances signaled embodied cognition (e.g., from the presence of conceptual metaphors). As mentioned, the three main types of conceptual metaphors are *metonymy*, *orientation*, and *ontology* (Lakoff & Johnson, 2003). Three researchers reviewed the transcripts to identify utterances containing these conceptual metaphors. We then analyzed the participants' touchscreen gestures (e.g., tap, pinch to zoom, etc.) that co-occurred with these utterances during each learning episode, to help us understand the role of these gestures in supporting collaborative making-meaning, as facilitated by embodied cognition. Our team conducted a thematic analysis on these examples, in which we discussed themes that emerged in terms of which types of gestures most often accompanied the conceptual metaphors and seemed to be essential in affording embodied cognition during collaborative meaning-making.

Findings

We present two over-arching themes that illustrate the types of gestures groups used to facilitate collaborative meaning-making when engaged in embodied cognition in our study.

Gestures for orienting the group

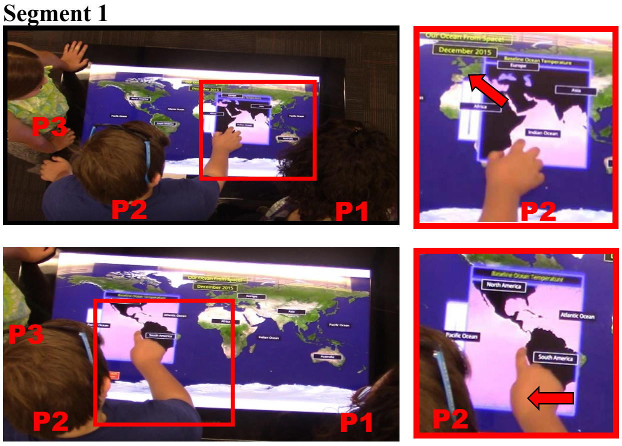
We observed that participants' interactions with the interface elements guided their thinking process and helped them orient themselves and the group to the science content displayed on the prototype. We saw that the physical affordances offered by the maskviewer element, such as being able to resize and move it around the tabletop, allowed participants to focus the group's attention on how temperatures change at various geographic locations. Segment 1 (Figure 2) is an example of this theme. We identified it as an instance of embodied cognition based on lines 4, 5, and 6. These utterances illustrate the use of *metonymic* conceptual metaphor, in which P2 and P3 [Group597] are speaking as if placing themselves physically into the world represented by the prototype: they are talking about the temperature change as if it was actually occurring, saying that "*It's really cold!*" and using words "*...out here in like the middle...*" even though P2 is not in the middle of the ocean himself. This segment shows how participants are dragging the maskviewer element to incrementally build their understanding of the temperature visualization by promoting discussion about temperature variations at specific geographic locations. In their gestures, P2 is dragging the baseline ocean temperature maskviewer element over the Indian Ocean, as he says, *"So check that out, that's very cold right there."* P2 further drags the maskviewer near the middle of the Pacific Ocean to compare the temperature patterns for the Indian and Pacific Oceans, as he says, *"So out here in like the middle of the Pacific Ocean, it looks like it's upwards of 88 degrees."*

We also observed that resizing the maskviewer helped focus the group's attention and facilitate collaborative meaning-making. Segment 2 (Figure 2) is an example of this theme. We identified it as an instance of embodied cognition based on line 2, which exemplifies a common type of ontological metaphor called personification: P2 [Group912] treats the prototype as a "storyteller" by saying that the prototype is "telling" them something. In their gestures, we see the group resizing the maskviewer to focus the group's attention and facilitate meaning-making. Initially, P2 [Group 912] directs P1 to re-size the maskviewer in order to focus on a specific geographic location, as he says: *"Let me see Florida ...Ya, shrink it and put it like right over the north east ... So, it tells what different temperatures are here or ...".* At this moment, P1 is using the maskviewer element as a tool to help direct the group's attention onto Florida and analyze how the temperature changes near it: *"Pretty warm."* The above examples show dragging and zooming gestures co-occurring with the utterances signifying embodied cognition. Thus, we can infer that participants were using the maskviewer element as an embodied lens for comparing temperature patterns through physical interactions with the prototype. Without the maskviewer, the data visualization would encompass the entire interface, making it more difficult to direct the group's attention and focus on subcomponents of the dataset before the group is ready to think at a higher level. Dragging and zooming the maskviewer and attending to what temperature patterns they reveal for different geographical locations seemed to push participants to focus on a subset of the data at a time as their conceptual understanding is constructed piece by piece. Therefore, future touchscreen interfaces for learning should support interactions that bring key aspects of the science content gradually into focus in this way.

Cooperative gestures for facilitating collaborative meaning-making

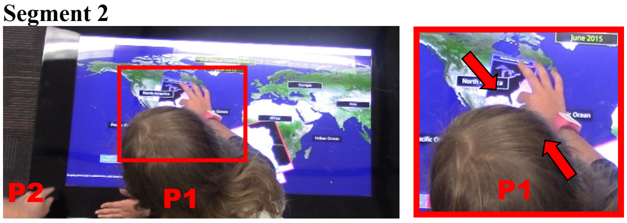
Another theme frequent in our analysis was participants using cooperative (multi-user) gestures to facilitate collaborative meaning-making. Morris et al. (2006) defined *cooperative gestures* as interactions in which the interface interprets the simultaneous gestures of more than one user as contributing to a single command. We observed that the interaction constraints offered by our time slider, in that it required simultaneous gestures (either using two hands or by two users at the same time), encouraged participants to actively participate in collaborative meaning-making through cooperative gestures. Segment 3 (Figure 3) is an example of this theme. We identified it as an instance of embodied cognition based on lines 5 and 6, which illustrates the use of *metonymic* conceptual metaphor: saying "*…go to…*" and "*…go ahead…*" to stand in for manipulating time within the visualization, as one cannot physically move to the time under discussion. This segment presents an example of how interface elements that allow users to interact cooperatively encourage group members to actively participate and contribute to the group's shared knowledge. In this example, initially, we see that P3 is passively watching P1 and P2 [Group247] interact with the prototype and discuss their observations, instead of actively participating and contributing to the group's understanding. We see later on (starting line 6) that since P1 is utilizing both of his hands (right hand for holding the slider and left hand to point towards the temperature pattern on the map), he looks at P3 to ask for help with changing months using the time slider by saying: *"Go to like, go to like May or June. That's April. Look how much warmer it's getting. That's June. Look how super warm it is."* Though P3 was just helping P1 change months, directly manipulating the prototype content helps P3 to focus on the temperature trends P1 and P2 were discussing. While P3 changes the month on the slider, he

Segment 1



1. **P1:** Yeah, yeah let's do the Indian Ocean *(dragging the maskviewer to the Indian Ocean).*
2. **P2:** So, check that out, that's very cold right there* *(dragging the maskviewer towards Europe and the top of Africa)*
3. **P1:** Woooow!
4. **P2:** Up in here it's pretty chilly too* †*(dragging the maskviewer towards the Pacific Ocean).*
5. **P3:** It's really cold†
6. **P2:** Find a really hot spot. So out here in like the middle of the Pacific Ocean, it looks like it's upwards of 88 degrees † **[Group 597]**

Segment 2



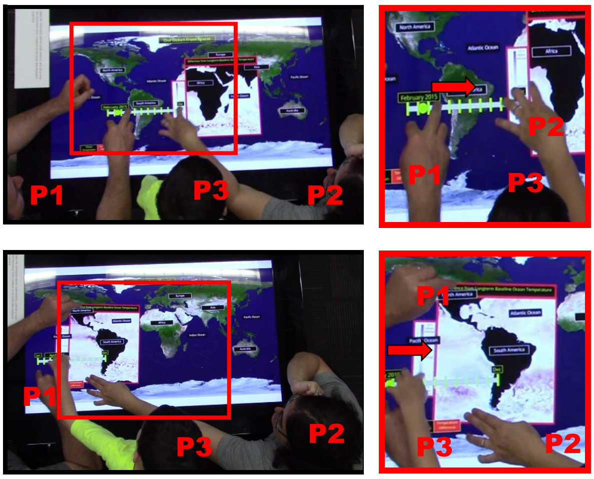
1. **P1:** Let me see Florida (*dragging maskview over Florida, then enlarging maskview*)
   … *(other talk)*
2. **P2**: Ya, shrink it (P1 shrinks maskviewer) and put it like right over the north east* (P1 drags the maskviewer over Florida). Here you go. So, it tells what different temperatures are here ‡ or ... *(P1 zooms in map over Florida)*
3. **P1:** Pretty warm **[Group 912]**

Figure 2. Example of a family group using the maskviewer to compare temperature patterns for geographic locations. The zoomed in view of the image on the right shows details of participants' interaction with the prototype. Participants' utterances signifying conceptual metaphors are noted: *metonymic*†, *personification*‡. Utterances marked with an asterisk (*) co-occurred with the gestures shown in the images.

starts contributing to the group's understanding by making inferences about how temperature patterns change at different geographical locations, as he says: *"But that's like in the middle. Here, let me show you."* Gestures can serve as a mechanism for cognitive offloading; that is, by taking up some of the cognitive efforts of attention and focus, they allow a learner to focus cognitive resources on other aspects of a task such as drawing inferences (Goldin-Meadow & Beilock, 2010). Furthermore, when working collaboratively on a complex task, reducing individual cognitive load and encouraging group members to exchange knowledge helps in collaborative knowledge-building (Kirschner et al., 2018). In their gestures, the participants work together in order to operate the time slider. P2 holds his hand on the screen in order for the time slider to pop up, while P3 drags the slider to different months. Thus, instead of having one participant focus their cognitive resources on operating the time slider, the group collaboration reduces the amount of cognitive effort required by each participant. Then, the participants can use more of their cognitive resources to engage in science discussion, seen in the utterance by P3, *"It's [temperature] near av- [average] that's where it was near average."* The above example illustrates that using cooperative gestures facilitates collaborative meaning-making by encouraging group members to engage in a scientific discussion together in a more hands-on and active manner.

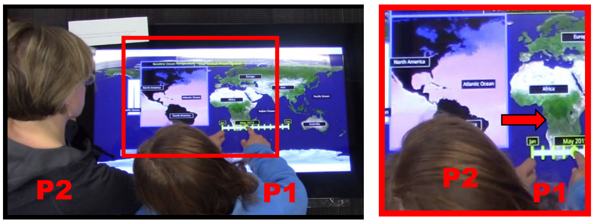
We also observed that interacting collaboratively allows group members to build upon each other's understanding of the temperature patterns. Segment 4 (Figure 3) is an example of this theme. We identified it as an instance of embodied cognition based on lines 2, 4, 5, 6, and 8, which illustrate the use of *metonymic* conceptual metaphor: participants talk as if they are actually experiencing the time and temperature change portrayed within the prototype, by saying, "*it's almost white now*". In this example, we see that P1 and P2 [Group765] are collaboratively interacting with the time slider. As P2 changes months, she says, *"It's definitely warm. June, warmer."* P1 further builds upon the group's understanding of temperature by saying, *"Definitely warm, it's getting closer to 95 [degrees]."* The group continues to change months on the time slider and watch the temperature change within the visualization. Finally, P1 says, *"it's almost white now."* Segment 3 demonstrates that participants are using cooperative gestures to discover the mapping between different scientific variables of the visualizations (i.e., what temperature the colors depict and how temperature changes with time). Both of these examples show cooperative gestures co-occurring with utterances signifying embodied

Segment 3



1. P2: No, that's a different. So wait no no no. So, oh yeah temperature wouldn't, this isn't precipitation.
2. P1: Well yeah, but I mean they are definitely related*. The issue that I see- *(long tap gesture to activate time slider, then dragging time slider with middle finger)*
3. P2: So warm and humid? So, if we move this over here *(dragging the maskviewer)*.
4. P1: Yeah.
5. P2: And go to, it was May, June, and July right? † (deactivates time slider by stopping long tap gesture) That it said El Nino was? ‡
6. **P1:** Was it? Okay. So, if we go till, yeah go ahead* *(long tap gesture to activate time slider)* and January the temperature isn't that much of a difference.† Go to like, go to like May or June *(P3 dragging time slider)*. That's April. Look how much warmer it's getting. That's June. Look how super warm it is. †
7. **P2:** Yeah but you would think if it's warm up there *(pointing gesture)* then that would cause rain over here because of warm humid air. †
8. **P1:** Depends on the wind pattern.
9. **P3**: But that's like in the middle (*pointing gesture*). Here, let me show you. (*deactivates time slider by stopping long tap gesture*) (other talk)
10. **P1:** July through October
11. **P3**: It's near av- that's where it was near average. **[Group 247]**

Segment 4



1. **P2**: Alright, what happens next? April.
2. **P1**: It's getting warmer* † *(dragging the time slider)* …
3. **P2**: It's definitely warm. June, warmer…
4. **P1**: Definitely warm, it's getting closer to ninety-five. †
5. **P2**: Yeah that's pretty warm. †
6. **P1:** Oh! Dang, that's getting warmer. †
7. **P2:** July's pretty hot.
8. **P1:** It's almost white now † **[Group765]**

Figure 3. Examples of family groups using cooperative gestures to construct collective working memory. The zoomed in view of the image on the right shows details of participants' interaction with the prototype. Participants' utterances signifying conceptual metaphors are noted: *metonymic*†, *personification*‡. Utterances marked with an asterisk (*) co-occurred with the gestures shown in the images.

cognition. Thus, we can infer that participants are using these cooperative gestures as a mechanism for cognitive offloading, and to focus their cognitive resources on meaning-making and drawing inferences related to how both time and space affect ocean temperatures. Without the cooperative gesture required by the time slider, participants would not need to coordinate to change the time period shown, making it more difficult to keep the group's understanding aligned. Using cooperative gestures seemed to push participants to create a collective working memory and encouraged group members to exchange knowledge. Therefore, future interactive learning experiences should encourage interactions that afford group members to cooperatively manipulate the interface elements like the time slider to facilitate embodied-cognition-supported learning.

Discussion, implications, and conclusion

Prior studies offer evidence in favor of using touchscreen interaction to encourage embodied-cognition-supported learning activities around tabletops, e.g., (Lin et al., 2016). However, these studies did not analyze what specific touchscreen gestures people make when engaged in embodied cognition, and whether these gestures are tied to particular instances of learning. We seek to understand how to support and encourage the types of gestures that accompany embodied cognition as revealed in learners' language. Based on Lakoff & Johnson (2003), in our study, we used linguistic cues from groups' utterances, in the form of *conceptual metaphors*, as signals that embodied cognition was occurring. We saw instances of embodied cognition reflected in groups' language in the use of both *metonymy* and *ontology* (i.e., *personification*): by speaking as if placing themselves physically into the world represented by the prototype and by speaking as if viewing the prototype as a "storyteller". During these types of utterances, groups made a variety of touchscreen gestures, including attention-focusing gestures and cooperative gestures. Groups used the maskviewer elements as an *embodied lens* to focus the group's attention on local areas of interest and guide their thinking process, by moving and re-sizing the maskviewers to reveal the underlying temperature patterns across different geographical locations. These interactions with the maskviewer pushed participants to focus on subsets of the dataset at a time as their conceptual understanding is constructed piece by piece. In the future, designers of such learning interfaces could consider ways to incorporate similar embodied lenses (not limited to maskviewers specifically) or even multiple embodied lenses within an application that bring key aspects of the science content into focus. These lenses could be manipulated by users to explore and compare multiple regions of multidimensional data visualizations through operations such as dragging and zooming (instead of just exposing the entire dataset at once) to facilitate scientific discussion. Also, cooperative touchscreen gestures add value to applications by increasing participation and enhancing the social aspects of an interactive experience (Morris et al., 2006). Our findings indicate a positive role of such cooperative gestures in supporting scientific discussion and collaborative meaning-making, from the viewpoint of embodied cognition. We saw that using cooperative gestures supports groups in creating a collective working memory by directing the group's attention towards the same focus point and encouraging group members to contribute to the meaning-making process. Thus, we believe our findings add to the field's understanding of the role of cooperative gestures in terms of showing both how they are involved in embodied cognition and how they support collaborative meaning-making. Future tabletop learning environments could encourage similar interactions that afford group members to cooperatively manipulate the interface elements to foster group learning, as in the case of multiple lenses above.

The instances of embodied cognition we identified in participants' language suggest that their interactions with the prototype and its data were immersive and sensory-based, as participants envisioned themselves as if they were physically "in" our prototype. This finding is consistent with theories of embodiment suggesting that learners' thoughts and understandings are shaped by their prior and ongoing physical interactions with the environment (Wilson & Golonka, 2013). The language metaphors and gestures we identified support future work into examining how embodied cognition underlies the interpretation of scientific content and processes in touchscreen-based learning environments. We disagree with Goldinger et al.'s (2016) critiques of embodiment utility as a theory. Those authors do not discuss learning, and we believe the value of being able to design affordances to support learning through embodiment will be strong. Our study points toward a need for a deeper investigation of designing with embodied cognition in mind, especially in the context of science content and practices. Identifying how embodied cognition actually manifests in both language and gestures in these types of experiences will allow us to design touchscreen interactions more targeted towards fostering embodied-cognition-supported learning. In our future work, we will continue to analyze our dataset for further themes, by considering other theories related to the role of both direct touch and in-air hand gestures in facilitating collaborative meaning-making (Goodwin, 2007). While our study presented a new view of designing tabletop interfaces by identifying the nature of gestures that occur during embodied cognition, future work should evaluate the effect of encouraging these gestures to determine how well they support learners' underlying cognitive processes in a real learning environment and expand this inquiry into other learning domains beyond data visualization and Earth's ocean temperature phenomena.

Endnotes

(1) http://openexhibits.org/downloads/sdk
(2) https://neo.sci.gsfc.nasa.gov/
(3) https://sos.noaa.gov/What_is_SOS/sites.php
(4) https://svs.gsfc.nasa.gov/2915
(5) http://www.bom.gov.au/, http://www.grida.no/resources/7045

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Acknowledgments

This work is partially supported by National Science Foundation Grant Awards #DRL-1612485 and #IIS-1552598. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect these agencies' views. The authors also thank the Florida Museum of Natural History for allowing us to recruit participants from their visitors. This work was conducted while author Jeremy Alexandre was a summer intern at the University of Florida.