Interface Tangibility and Gesture in Mediating Individual Agency Within Group Spatial Problem Solving With an Ecosystem Simulation

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Abstract: This paper examines how a tangible interface facilitates gesture-mediated spatial reasoning during collaborative problem solving, as evidenced by sensitivity to emergent spatial patterns within a complex system simulation of a watershed. We tested the interface against two non-tangible input comparison conditions (single- and multi-mouse) to control for access differences. To determine if groups' solutions displayed sensitivity to emergent spatial patterns, we constructed a quantitative "dynamism" measure, and found that solutions produced in the tangible condition were significantly more spatially sensitive. To better understand why, we conducted a case study by selecting two representative participant groups and performing qualitative multimodal analyses of participant speech and gesture. Our findings indicate that the tangible interface's greater affordance of gesture allowed participants to express concepts containing both spatial and temporal properties, with the added benefit of increasing the agency of less-verbally participatory group members to explore and contribute their ideas more equitably.

Introduction

When a complex system simulation is spatial, meaning that the location of simulation elements has an impact on the emergent outcomes of the simulation, special supports may be needed to assist learners as they come to reason spatially about the represented domain. By "reasoning spatially," we do not refer to classic visuospatial cognition literature (e.g., wayfinding or mental rotation tasks), but rather to the class of problems identified by the NRC Committee on Geography's (2006) "Learning to Think Spatially" report, wherein reasoning spatially entails the ability to "perceive, remember, and analyze the static and, via transformations, the dynamic properties of objects and the relationships between objects." In our problem space (the integration of green infrastructure into urban landscapes) spatiality is highly important: a given green infrastructure element may have a large impact or none at all depending on its placement. Because traditional desktop simulations ask the user to transmute spatial manipulations through (single-user) input devices like mice, we designed a tangible simulation interface to support more direct spatial manipulations by multiple users and conjectured that the tangibility would improve users' abilities to construct solutions sensitive to the simulation's emergent spatial phenomena. We tested the interface against two non-tangible mouse input conditions, and gauged sensitivity of solutions with a "dynamism measure"- finding that solutions produced in the tangible condition were significantly more spatially sensitive. A case study was then conducted to examine why, and our findings, which are presented in this paper, indicated that the tangible interface afforded gesture-mediated spatial reasoning, which enabled less verbally participatory group members to better consider spatial and temporal information and more equitably express their reasoning, resulting in improved group problem solving outcomes.

Prior Work

In human-computer interaction research, tangible user interfaces (TUIs) in the form of multi-touch tabletop displays have been shown to result in more equitable participation by group members working on tasks with spatial or other physical constraints, like arranging office seating (Marshall et al., 2008) or planning itineraries (Rogers & Lindley, 2004). In a study that compared a multi-touch tabletop to input using TUIs, the use of tangibles encouraged greater participation from people who normally found it difficult to contribute verbally in group settings (Rogers et al., 2009). Other research has found that the use of TUIs facilitated individual spatial problem solving as users leveraged the physical affordances of tangible objects (Antle et al., 2009). This research adds to this prior literature by examining the affordance of TUIs for gesture-mediated spatial reasoning in the context of group spatial problem solving with a dynamic, computer-based simulation.

There is a growing body of research on the role gesture plays in facilitating spatial cognition (Alibali, 2005; Goldin-Meadow, 2003). There are various dimensions or types of gesture that have been identified, including deictic (pointing) and iconic gestures (McNeill, 1992). Iconic gestures are considered 'representational' as they present kinesthetic images of objects or actions; for example, waving a cupped hand up and down while talking about playing basketball. Iconic gestures can thus facilitate spatial cognition by helping the gesturer to focus upon and represent dynamic, temporal and spatial information—information that would be difficult to convey in speech but that is necessary for understanding a topic (Pozzer-Ardenghi & Roth, 2007). In fact, gesture appears to provide a visuospatial modality for learners to explore ideas that cannot yet be articulated in speech because the domain is new or the conceptual vocabulary has not been acquired (Alibali & Goldin-Meadow, 1993; Roth & Welzel, 2001). In research on computer-supported collaborative learning, gestures have been acknowledged as an important resource for knowledge building although the focus has primarily been on deictic gestures for establishing joint attention and shared reference (Stahl, 2003). Studies of small-group science inquiry have examined both deictic and iconic gestures, and found that iconic gestures in particular can provide support for spatial reasoning and representation of information that could be shared and negotiated by the group (e.g., Radinsky et al., 2008; Roth & Lawless, 2002). The studies by Radinsky, Goldman, and Singer (2008; Singer et al., 2008) also examined tracing gestures, although traces were grouped with deictic gestures, thus highlighting their indexical function. Tracing gestures can have both deictic and iconic elements (Goodwin, 2003), and in this study we use the term "iconic-tracing" to highlight the dual function of such gestures to publically index an object visualized in the environment, and to represent the visuospatial or dynamic characteristics of the object.

Study Design and Methods

29 triads (mostly undergrads and high school students) were given the task of creating optimal rainwater infiltration solutions by placing gardens, called swales, on an urban map. Groups were given twelve minutes to create multiple swale configurations, which they tested by viewing a simulation based upon their placements. The groups had to balance ground rainwater infiltration against swale cost. To achieve a high combined score, the participants had to become more effective at placing swales in locations that would more efficiently capture more of the rainfall. The rain fell evenly across the map in the simulation, but the combination of ground elevation and man-made features (like paved roads and water-diverting sewers) produced emergent flows and pools of surface water. Participants could see these flow paths and pools by watching the simulation's visualization as it ran. A simulation run terminated automatically when there was no longer any surface water (having either drained into sewers, infiltrated into the groundwater supply via swales, or flowed off of the map through a "sink" - a low-elevation point at the edge of the simulated map).

Groups performed this task in three input conditions (tangible interface, single-mouse, and multi-mouse). A repeated-measures-with-rotation design was used to alternate the order of input conditions as well as to alternate the specific urban maps. Participation was incentivized by cash paid to each member based on the distance of the group’s best combined infiltration and swale cost scores from the ideal solution. In the tangible interface condition participants were given physical tokens representing swales that they could place on a paper map representing the landscape. An overhead camera recorded the configurations and sent the input to a computer which ran the simulation for the participants to view on a display placed behind the map. In the mouse input conditions, participants used one or three mouse controllers to place swales on the landscape represented on the screen of a shared laptop. The results of all configurations were exported at the click of a button to the simulation computer, so in all conditions the simulation run was witnessed at the same viewing angles and screen size. The three maps given to participants were determined to be equally difficult but different in surface details to mitigate a practice effect.

We wanted to know whether or not the participants became any better at placing the swales in response to the observable emergent patterns in surface water flow, so we constructed a "dynamism" measure for each grid square on each map. We defined "dynamism" to be the amount of water inflow each grid square received from its neighbors over the length of the simulation run, in gallons, which we then normalized by dividing by the highest inflow value obtainable on that particular map (these maximum values were roughly equivalent across the three maps). To assess participants' placements in a particular trial, we computed an average normalized dynamism value, summing the normalized dynamism values of all of their chosen swale locations and dividing by the number of swales placed. A higher average normalized dynamism value indicated that participants were placing swales in locations that were more effective at trapping water for infiltration, whereas lower dynamism values indicated that participants were less successful in placing their swales in locations that would intercept surface water. We noticed that participants produced solutions that had higher average normalized dynamism in the tangible condition than the other conditions (see results section) which prompted us to select two representative cases to examine more deeply.

All sessions were videotaped in order to quantify the number of different configurations and qualitatively analyze the conversations and actions. For the case study (Yin, 2003), we selected two groups that were representative of the higher average normalized dynamism observed in the tangible condition, but which were different in all other ways. They were of different age groups (undergraduate vs. high school) and genders (males vs. females), and experienced the tangible condition in opposite order (tangible, single mouse, multi-mouse vs. single-mouse, multi-mouse, tangible). They also showed different relative dynamism values for single-mouse and multi-mouse (higher for single-mouse in Group 1, higher for multi-mouse in Group 2) despite their mouse conditions being ordered identically (single-mouse followed by multi-mouse). We transcribed and coded the videotaped sessions for the two groups using a multimodal format adapted from Goodwin (2003) in order to examine both speech and gesture. We also segmented participants' speech into *utterances* following a procedure similar to Kintsch (1998) where each utterance is defined as a meaningful unit that expresses a proposition or sentiment. Therefore, even when a participant expressed agreement through a single word (e.g., "okay") in a single conversational turn, this was counted as an utterance. Utterances were then coded for evidence of contributions to collaborative problem solving for the following categories: 1) asserting an idea, 2) expressing agreement, and 3) expressing disagreement.

Gestures were annotated following a procedure modified from McNeill (1992) for their timing with utterances, type, and description. Gesture types included deictic, metaphoric, iconic, and iconic-tracing gestures. As explained earlier, we added an "iconic-tracing" category to emphasize *both* the emergent deictic aspect for actively pointing out references, and the iconic aspect to describe the visuospatial or dynamic characteristics of the references. Iconic gestures were distinguished by their holistic representation of an object, whereas iconic-tracing gestures were distinguished by their schematic use to trace out the shape or flow of an object. Purely iconic and metaphoric gestures did not appear significantly in the data and are not included in the analysis.

Findings

In this section, we first present the overall quantitative dynamism results, followed by the qualitative findings for Group 1 and Group 2. These cases are presented separately with an overview of the three sessions' group dynamics and gesture use, followed by a more detailed presentation for the tangible interface session. In the final section, Groups 1 and 2 are discussed together. Note that group members are referred to by the Red, Green, or Yellow color wrist bands worn during the sessions (e.g., Group 1 members are Yellow1, Green1, and Red1).

Quantitative Dynamism Results

The average normalized inflow values seen across all 29 groups of three participants was 0.074 ($SD = 0.087$) for paper, 0.065 ($SD = 0.088$) for multi-mouse, and 0.046 ($SD = 0.045$) for single-mouse, which showed a significant effect of interface style on the ability to target high-dynamism locations for swale placement [$F(2,581) = 7.15$, $p < 0.001$]. Post hoc comparisons using the Tukey HSD test indicated that the paper condition differed significantly from the single mouse condition ($p < 0.01$), although there were no significant differences between the paper and multimouse or between the multimouse and single mouse conditions.

Group 1 Overview of Three Sessions

Group 1 consisted of three male college students. The order of conditions that Group 1 received was: 1) tangible interface, 2) single mouse, and 3) multi-mouse. Table 1 below presents numeric summaries of the communicative output across the three conditions. From this data, it is evident that Yellow1 dominated for utterances in every session, and for gestures in the second and third sessions—although mostly with deictic gestures. Red1 produced the most gestures in the first session with many iconic-tracing gestures, but both his utterances and gestures dropped precipitously over the following two conditions. Green1 consistently produced a moderate number of utterances and smaller number of mostly deictic gestures, and appeared to grow more assertive over the three sessions.

Table 1. Group 1: Communicative output per condition

	Tangible Interface			**Single Mouse**			**Multi-Mouse**		
Data	Yellow1	Green1	Red1	Yellow1	Green1	Red1	Yellow1	Green1	Red1
Total # of Utterances	74	47	55	54	32	23	73	65	56
Asserting Idea	10	8	5	11	9	3	9	8	4
Express Agreement	7	4	16	8	5	10	7	5	15
Express Disagreement	4	4	3	4	4	1	3	4	3
Total # of Gestures	13	7	16	11	7	3	7	2	2
Deictic	10	6	9	8	7	3	7	2	1
Iconic-tracing	3	1	7	3					1

Fortunately the video data provides rich detail about how Red1's iconic-tracing gestures helped him to consider dynamic spatial information, and assert his ideas verbally to the group. As will be described further below, Red1's assertion of his main idea in the tangible interface session also effected an interesting moment of convergence and agreement in the group.

Group 1, Session 1: Tangible Interface

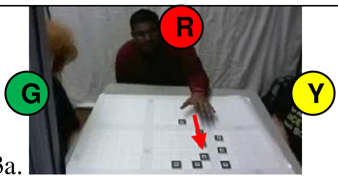
In Group1's first trial, Yellow1 led by stating his understanding of the pattern of rainwater absorption he observed in the first run of the simulation, and by correcting Green1's orientation, who then realized he had incorrectly transposed the landscape visualized on the simulation screen to the landscape represented on the paper map. Yellow1 also initiated placing the first swales and suggesting that they pursue a strategy of either lining a street with swales or alternating swales in a checkerboard pattern (see Table 2, line 1). Green1 immediately joined Yellow1 in placing swales, but Red1 hesitated and made his first assertion (line 2) which was not picked up by the others to spread out the swales more. This early group interaction (Table 2) shows Yellow1 and Green1's agency in action and Red1's attempt to make an assertion which was ignored. Also, Red1 provides an early verbal expression of an idea about 'spreading' that he only reasserts successfully later after first inscribing it in gesture.

Table 2. Group1: Articulating first ideas and actions.

1	[02:18.20] Yellow1: (*Yellow1 and Green1 are placing swales on map as Yellow1 is talking*) So we should create this and see if we just need lines? Or do we want to alternate? [02:23.04]
2	[02:23.05] Red1: Or do you wanna spread em out maybe?... [02:25.00]
3	[02:25.13] Green1: Actually [02:26.03]
4	[02:26.10] Yellow1: Or to go, go opposite?[02:26.19]
5	[02:33.00] Green1: We also got quite a bit over here [02:33.08]
6	[02:36.04] Red1: (*Still has not made any placement yet)* Yeah (*pause*) should we...[02:40.23]

Over the next trial, Red1 produced gestures as if considering the flow of water over the landscape but accompanied by minimal or no speech. Such gestures indicate that they were made *for thinking* (McNeill, 2005) rather than for speaking. In Table 3, frame 3a (below), Yellow1 had just finished pointing out how the water ends up in the lower left quadrant of the map (not pictured) when Red1 moved his left hand in a wave-like motion to start an iconic-tracing gesture at [06:41.01] before he actually spoke at [06:42.20] saying only, "and um…" Through this gesture, Red1 appeared to be considering the emergent flow of water as he held his left hand palm down and fingers splayed out, moving over the line of swale placements down towards the left quadrant Yellow1 had just pointed out.

Table 3. Red1 Gestures for thinking examples.

3a. 	3b. 
[06:41.01] Red1: {**…** and um…} (*Red1 iconic-tracing gesture, starts speaking at [06:42.20]*)	[08:48.20] Red1: {um **I don't feel like**…} (*Red1 iconic-tracing gesture*)

Two minutes later in Table 3, frame 3b (see above), Red1 moved his left hand out along the left line of swale placements again and said, "um I don't feel like…" With this iconic-tracing gesture, Red1's palm is vertical to the map and loosely cupped, as if both considering the impact of the water flow down the street and how much could be contained (cupped image) in this area. Table 4 below shows how Green1 then asserted a disagreement with the current configuration (line 1), which gave Red1 an entry for asserting his idea leading in with a pointing gesture (line 2) before speaking (line 4). As soon as Red1 pointed out the area of concern (lines 4, 5), there was an immediate convergence of overlapping speech, agreement, and pointing gestures by all three group members. Red1then more fully articulated his idea for spreading out the swales (line 9), and making it "a gradual change" (lines 15, 16), which echoed his initial assertion that was ignored at [02:23.05] (Table 2) to "spread them out." However, Red1's idea and reasoning is more clear here, and presented an effective spatial strategy for reducing the emergent water flow to the zone that Yellow1 and Green1 had lined with a checkerboard of swales.

Table 4. Red1 articulates idea of "spreading" and "gradual change."

1. [08:48.24] Green1: There's a little bit too much. 2. [08:49.20] Red1: {**Yeah**} *(moving right hand in, pointing gesture);* 3. [08:50.21] Yellow1: Okay. 4. [08:54.04] Red1: …{So let's, um, **right here** like, right here} (*long pause*)		
		
5. [08:56.04] Red1: [{seems like **right here**}]. 6. [08:56.04] Yellow1:[{**These two** are neighboring}]. 7. [08:56.10] Green1:[{**Yeah**}]. 8. [08:56.20] Red1:[{They're so close] and **that's neighboring**}	9. [08:58.10] Red1: that we could easily just take it away (*pause*) 10. [09:00.17] Red1: [like that]. 11. [09:00.17] Green1: [also, it didn't seem] to have much of an effect in that area.	12. [09:04.14] Yellow1: Let's spread this out maybe, we can get rid of this one? 13. [09:07.16] Green1: Yeah seems like that would be better *(Red1 and Green1 look up and check the simulation).*
		
14. [09:10.22] Red1: Yeah {because its **concentration is centered** here}	15. [09:12.00] Red1: at least make {it like a **gradual** (*pause*) **change**}.	16. [09:13.26] Yellow1: Mm-hm (*agrees*).

Group 2 Overview

Group 2 consisted of three female college students. The order of conditions that Group 2 received was: 1) single mouse, 2) multi-mouse and 3) tangible interface. Table 5 presents a summary of the communicative output for all three conditions. From this data it appears that Green2 dominated in every session for utterances, but gestured only in the first two mouse input sessions with mostly deictic pointing gestures. Yellow2 was consistent over the sessions but produced more utterances and gestures in the mouse conditions than Red2, who was inconsistent by producing many utterances in the first session (although few gestures because she was in control of the single mouse), but then dropping in utterances and gestures in the second session. In the third session, Red2 dramatically increased her number of utterances and produced a large number of iconic-tracing gestures, unlike her partners.

From the video data for Group 2, it is evident that Red2 began to use iconic-tracing gestures in the third (tangible) session to better articulate her thinking about the emergent spatial flows of rainwater. Over the three sessions, Red2 appeared to have difficulty in verbally articulating her spatial reasoning, but by the tangible interface session, Red2 became more insistent and better able present her ideas using iconic-tracing gestures as a support.

Table 5. Group 2: Communicative output per condition.

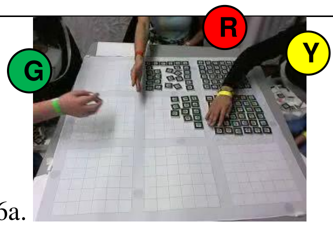
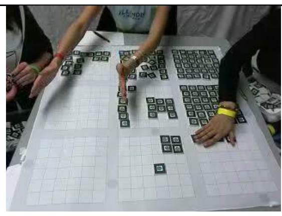
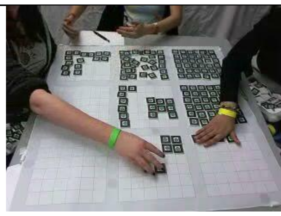
	Single Mouse			Multi-Mouse			Tangible Interface		
Data	Yellow2	Green2	Red2	Yellow2	Green2	Red2	Yellow2	Green2	Red2
Total # of Utterances	60	103	89	69	126	38	40	93	78
Asserting Idea	11	18	6	5	16	5	6	18	13
Express Agreement	9	5	8	8	5	5	9	5	8
Express Disagreement	1	6	2	0	7	2	1	14	8
Total # of Gestures	23	42	4	10	14	5	5	13	26
Deictic	21	35	2	9	12	3	5	13	12
Iconic-tracing	2	7	2	1	2	2			14

Group 2, Session 3: Tangible Interface

In this session, Green2 made the first move by asserting her idea of placing swales on the "dark spots" (i.e., low elevation locations) which led to a strategy pursued by all three group members to fill up an entire quadrant on the map with swales, creating a catchment effect (where water would pool over a cluster of swales). However, after viewing the simulation results from the initial swale configuration, Red2 referred to the edge of the map closest to her and tried to assert a different idea. At [07:12.03] she said, "Let's just try…" but because Yellow2 and Green2 were busy talking, she went ahead and started placing swales near her edge. Red2 was more specific at [08:29.26] with, "I don't know... I really want it along the edge though right here (*pause)* really, really, really want that!" However, when Red2 added iconic-tracing gestures, she started to elucidate her reasoning.

Table 6 below provides examples of these gestures and the added spatial information that supported her reasoning. At [08:48.03] (Table 6, frame 6a), Red2 first argued, "Because I saw the water coming down like this," while moving her right hand in a waving motion over the middle section of the paper map towards her edge. About 20 seconds later (not pictured in Table 6), Red2 then repeated this gesture for herself without speaking. By [12:13.21] (Table 6, frame 6b), Red2 had picked up more emergent information about the water flows and used two hands to trace the flows down farther along the right side of the map, and then with two cupped hands to move along her edge. Red2 was more sensitive to the location of the flows now and why there was so much pooling towards her edge. While Green2 had been consistently arguing against Red2's concern for the edge, by [14:03.04] Green2 gave in and agreed, although out of friendly exasperation, "Alright! Just try things!" In Group2, although there wasn't a clear moment of group convergence, Red2's use of iconic-tracing gesture enabled her to sensitize to emergent spatial flows in the system and better articulate her spatial reasoning, which perhaps gave her the confidence to keep asserting her ideas until they became incorporated by the group.

Table 6. Red2 adds spatial information to her gestures.

 6a.	 6b.	 6c.
1. [08:48.03] Red2: Because I saw the water coming down like this.	1. [12:13.21] Red2: The water at the end was towards the edges…	2.[12:14.11] Red2: …and onto the streets. 3.[00:12:19.05] Red2: I don't think it was up there though (*to Yellow2*).

Discussion

As mentioned earlier, we chose Groups 1 and 2 to compare on the basis of having similar dynamic outcomes despite different factors like age or gender or receiving the tangible interface condition in opposite order, which potentially rules out the effect that familiarity with the task would have on participant performance in a given input condition. Nevertheless, we found similar interaction patterns in the tangible interface condition for the two groups in that the least dominant group member of each group, Red 1 and Red2, experienced failure at first in articulating and asserting their ideas verbally, but then succeeded after using iconic-tracing gestures to pick up and describe emergent spatial information. What were the particular representational affordances of the tangible interface that enabled this iconic-tracing gesture based spatial sensitivity and reasoning? In both cases, it appeared that Red1 and Red2 visualized patterns of water flows *over* the paper map, indicating that the paper map provided a material support for their visualization. From a distributed cognition framework, Hutchins (2005) describes how material forms serve as *material anchors* for stabilizing conceptions, and the paper map appeared to serve this function. Similarly, the physical swale tokens also provided material anchors for visualizing water infiltration strategies. The physicality of the tokens may even have provided a representation of depth to the landscape. In fact at one point, Red2 began to stack the physical swale tokens on top of each other because she wanted to address the greater need an area where water was pooling. But even given the ways that the tangible interface functioned as a material anchor, it was nevertheless the use of iconic-tracing gestures that coordinated between what would be a mental visualization and the material anchor for the visualization. This coordinating function of gesture in bridging between the imagination and the material world has been noted in cognitive linguistics studies (e.g., Williams, 2008), and deserves further attention in educational technology design research.

Another similarity between Red1 and Red2 was their focus upon the pattern of emergent water flows over the landscape, although Red1 identified a different spatial strategy than Red2. Red1 expressed a "spread out" idea that reflected a sponge-like solution, anticipating the flow of rainwater and absorbing it as early as possible through a gradual distribution of swales. Red2 expressed a barrier-like solution of adding a cluster of swales to a point right before her catchment area to absorb and redirect the influx of rainwater. In fact, there was actually no single best solution for the rainwater infiltration problems presented to the groups because solutions depend upon both fixed landscape features like the gradients, streets, and sewer locations as well as the dynamic swale placements (e.g., the swale "barrier" Red 2 created in Table 6, frame 6b served to both absorb and divert the surface flow into her catchment area). Therefore the better solutions could only come about through sensitivity to emergent patterns of water flow observed in the simulation, which entails a sensitivity to how patterns unfold over time.

The positive impact of both Red1 and Red2's contributions to group spatial problem solving in the tangible interface condition was also evident in the quantitative dynamism measures (Table 7). The dynamism values are highest for both groups in the tangible interface condition, mirroring what was seen across the 584 trials generated by the other 81 participants in the study. For Group 1, the effect of the interface is significant according to a one-way ANOVA [$F(2,14) = 138.76$, $p < 0.0001$], with a *post hoc* Tukey HSD test confirming significance for Tangible vs. Single-mouse ($p < 0.01$), Tangible vs. Multi-mouse ($p < 0.01$), and Single-mouse vs. Multi-mouse ($p < 0.01$). For Group 2, although the interface condition did have a significant effect [$F(2,23) = 11.26$, $p < 0.001$], this held only for the Tangible vs. Single-mouse ($p < 0.01$) and Multi-mouse vs. Single-mouse ($p < 0.01$).

Table 7. Dynamism measures: Groups 1 and 2.

Group 1			Group 2		
Session 1: Tangible	Session 2: Single mouse	Session 3: Multi-mouse	Session1: Single mouse	Session 2: Multi-mouse	Session 3: Tangible
0.0464	0.0246	0.0181	0.0077	0.0270	0.1108

Implications and Conclusion

This study's findings indicate that a tangible interface provides a beneficial affordance for gesture-mediated spatial reasoning, especially for less verbally participatory or assertive group members in the context of group solving of a complex spatial problem modeled on a computer based simulation. As a modality for spatial reasoning and communication, gesture (and iconic-tracing gesture in particular) increased the communicative agency of less dominant group members and resulted in equalizing group participation. In addition, the greater sensitivity to emergent spatial information that these less dominant group members articulated through gesture first and then speech had the effect of improving group spatial problem solving performance. While the role of gesture in spatial reasoning and group communication has been studied before, we have focused on the particular benefit of iconic-tracing gestures for working with emergent patterns, and how a tangible interface supported such gesture use.

We speculate that the materiality of the elements of the tangible interface, including the paper map and physical tokens, provided a *material anchor* (Hutchins, 2005) for stabilizing what would otherwise be only mental visualizations of emergent water flows and varying spatial features of urban landscapes, and that iconic-tracing gestures provided the bridge to link participants' visualizations to these material anchors. Understanding tangible interfaces in terms of material anchors and the use of gesture brings useful elements from distributed cognition and cognitive linguistics frameworks into the design of interfaces for computer based group learning.

Recently, several studies have demonstrated that students who were required to imitate the gestures that a teacher performed for solving algebraic math problems did significantly better on subsequent tests than controls, and researchers speculated that the visuospatial reasoning strategies inscribed in gesture provided the benefit (Goldin-Meadow et al., 2009). To extend our current findings, we propose to borrow this strategy of intentional gesture by testing the current simulation in science classrooms with teachers intentionally modeling specific iconic-tracing gestures when introducing the simulation to students. In addition, teachers could simultaneously add conceptual vocabulary to the gestural communication (e.g., words such as 'surface flow' and 'catchments'), which would ground the terminology in relevant multimodal imagery (Alibali & Nathan, 2011). Similarly, another possibility for future research is to design a tangible interface that necessitates the performance of iconic-tracing type gestures for manipulating the spatial parameters of the ecosystem simulation. The one implication that is important to communicate from this study is that both individual group members and rest of the group can be helped by more opportunities to draw upon the dual function benefits of iconic-tracing gesture for both actively reasoning about emergent spatial phenomena and communicating and coordinating the reasoning with others. The emergent properties of complex systems have proven to be challenging for many learners (Sweeney & Sterman, 2007) and if gesture can provide an integral modality for reasoning about emergent phenomena, then the design of educational interventions—whether in the form of teacher communication strategies or tangible interfaces for computer based simulations—should consider how iconic-tracing and other types of gestures can play a role.

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