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Design Strategies for Collaborative Learning in Tangible Tabletops: Positive Interdependence and Reflective Pauses

Alyssa Friend Wise[1], Alissa N. Antle[2,*] and Jillian L. Warren[2]

[1]*Learning Sciences & Educational Technology, New York University, NY 10003, USA*
[2]*School of Interactive Arts and Technology, Simon Fraser University, Surrey, British Columbia V3T 0A3, Canada*
**Corresponding author: aantle@sfu.ca*

This mixed methods study examined the impact of two design strategies on interactional processes in a collaborative tangible-tabletop land-use planning simulation. Twenty pairs of fifth grade children used the simulation to create a world they would want to live in. To investigate the impact of positive interdependence half the pairs were assigned one of two roles, each with an associated set of tangible 'land-use' stamp tools. All pairs were given access to pause and reflect tools. Quantitative results showed that children in the positive interdependence condition gave more one-way explanations to their partners than control pairs. They also had fewer but longer instances of bilaterally resolved conflict. Qualitative findings indicated the importance of pause and reflect tools for provoking explanations and resolving conflict. This study has revealed important considerations for the instantiation of positive interdependence and reflective pauses in collaborative tabletop learning systems, showing both quantitative and qualitative differences in the interactional processes that result from these design strategies.

CCS CONCEPTS.
Human-centered computing → Empirical studies in collaborative and social computing.

RESEARCH HIGHLIGHTS

- This paper presents an in vivo experimental study of the effects of positive interdependence and reflective pause design strategies for creating collaborative learning applications on tangible tabletop platforms;
- The findings from a mixed methods analysis explicates how these design strategies stimulated interactional processes, including explanation giving and conflict resolution, that support learners to reach common ground in a collaborative learning task;
- The *positive interdependence* design strategy of creating system contingencies through tightly coupled tangible inputs combined with leveraging social practices related to assignment of roles and tools was associated with more explanations involving externalization of thinking, world inhabitant perspective taking and strategic level joint problem solving of conflict;
- The *reflective pauses* design strategy of having several universally accessible tools that could be used to stop interaction and provide world state information was associated with learners taking actions to jointly explore the task and come to better understandings of the task and each other's perspectives as they negotiated toward common ground;
- While the insights from this work are situated in the design space of tangible tabletops, which are characterized by hybrid physical–digital systems and embodied interaction, the findings can likely be generalized to other hybrid, embodied technology platforms (e.g. augmented reality, virtual reality) that are currently gaining momentum in the space of collaborative learning.

1. INTRODUCTION

As computation increasingly moves off desktops and laptops and becomes integrated into objects and environments in our lives, it is important to understand collaborative learning in the design space of hybrid physical and digital environments (mixed reality). There is a plethora of hybrid, embodied technology platforms that support social–physical–digital forms of interaction in space, for example, augmented realities, virtual realities, tangible tabletops, interactive spaces, networked hand-held devices, augmented maker workshops, automobile user interfaces, human–drones systems, interactive surfaces, as well as other emerging platforms. We focus on tangible tabletops—an early and prototypical example of a hybrid, embodied platform for collaborative learning. Interactive tabletops are horizontally oriented digital surfaces that allow for direct physical interaction with digital media through multi-touch and/or tangible objects (Antle, 2014; Higgins *et al.*, 2011). Tangible objects (or simply 'tangibles') are digitally augmented physical objects that are recognized by, can affect and can be affected by the tabletop system (Ullmer and Ishii, 2000). When they were first introduced, interactive tangible tabletops were highlighted as a technology particularly suited for collaborative learning due to their ability to support simultaneous use, hands-on activities and multiple modes of communication (Dillenbourg and Evans, 2011). While tabletops have not yet been widely adopted in classrooms, recent analyses suggests that they fulfill an important gap in learning technologies (Müller-Tomfelde and Fjeld, 2012). Specifically, they have been suggested to have particular affordances for facilitating joint attention and a shared transaction space for reference, negotiation and action (Antle *et al.*, 2011; Fernaeus and Tholander, 2006; Winoto and Tang, 2019; Woodward *et al.*, 2018). Of course, opportunities for collaboration are not always taken up by learners; the literature contains numerous examples of interactive tabletops being used in undesired ways including independent parallel play, competition and domination by one learner (Falcão and Price, 2011; Jamil *et al.*, 2017; Marshall *et al.*, 2009). Thus, two central challenges in designing tangible tabletop applications for collaborative learning are finding ways to distribute activity across a group and getting group members to coordinate this activity by engaging with each other productively (Higgins *et al.*, 2011; Roldán-Álvarez *et al.*, 2020). These challenges also apply to many other instances of mixed reality technologies that enable social–physical–digital interaction. As such, strategies to address these challenges in the context of interactive tabletops may generalize to interaction and learning design for other hybrid, social and embodied technology platforms in which small groups of people interact with each other, with objects and with computation in a spatial environment.

In this paper, we investigate how specific design strategies for tangible tabletop systems create affordances to support the interactional processes of collaborative learning, conceptualized as activities that support the negotiation of common ground. The design strategies we pursue involve creating affordances and/or opportunities for positive interdependence and encouraging reflective pauses. The focus of our experimental investigation was on positive interdependence, a well-known learning design principle in collaborative learning (Johnson and Johnson, 2014). Positive interdependence refers to the extent to which group members must rely on each other for effective actions. The main goal of the study was to investigate our proposed interaction design strategy (which included both technical and social components) for supporting positive interdependence in tangible tabletops. We also evaluated a second learning design principle for mixed-reality environments: encouraging reflective pauses. Encouraging reflective pauses refers to approaches that both provide a reason to reflect and offer the time to do so (Antle, 2014; Price *et al.*, 2010). Based on prior work, we hypothesized that reflective pauses are important for creating opportunities for negotiation in collaborative learning and therefore this design strategy must be considered as part of the enabling conditions for our investigation of positive interdependence (Antle *et al.*, 2011; Antle and Wise, 2013).

To investigate the instantiation of these two design strategies for tangible tabletops and their effects on collaborative learning processes we built a sustainability simulation called Youtopia. Youtopia lets learners build a world they would want to live in, taking into account both human needs and environmental conditions. We chose the domain of sustainable land-use planning because (i) it is inherently spatial and thus well suited to the large tabletop display surface; (ii) the topic is complex with many inter-relationships making it well suited to a simulation (Antle *et al.*, 2011); and (iii) it involves individual and societal values, thus able to benefit from collaborative negotiation processes about not only how goals should be achieved, but also which of multiple viable goals are worth achieving (Suthers, 2006).

The study reports on an explanatory mixed methods study (Creswell and Clark, 2011) with an experimental manipulation of our design strategy for positive interdependence (called 'roles') of 40 fifth graders using Youtopia. Quantitative analysis was used to investigate *whether* our design strategies supported the desired interactional processes of working together, explaining reasoning and resolving conflict jointly, while qualitative examination extended these findings by probing *how* and *when* they did so. While explanatory mixed methods studies often collect separate data for the quantitative and qualitative aspects of the work, this kind of design can also be enacted through the use of a single data set that is analyzed first quantitatively and then qualitatively. The results of the quantitative analysis can be used to produce the sample for the qualitative analysis (for examples, see Paulus and Wise, 2019; Rasmussen, 2015; Wise *et al.*, 2020). An important contribution of this work is understanding the ways that learners interact with technological tools that were designed to support positive interdependence and encourage reflective pauses in collaborative learning. In previous publications (*removed for blind review*) we focused on a subset of constructs and data and framed findings mainly from a learning sciences persective rather than that of design. In this paper, we draw on and extend those findings, reporting on additional constructs and data (e.g. qualitatave analysis of conflict-resolution events) and framing findings from the perspective of design guidance for collaborative learning.

2. COLLABORATIVE LEARNING AND TANGIBLE TABLETOP DESIGN

Understanding the affordances technologies offer for meaning-making is foundational for computer-supported collaborative learning (CSCL) (Jeong and Hmelo-Silver, 2016; Rosé and Dimitriadis, to appear; Suthers, 2006). Specifically, we focus on investigating practices of meaning-making through understanding negotiation processes and the ways in which these are mediated by design (Stahl and Hakkarainen, to appear). With tabletops, the artifact is a large horizontal surface with which learners can interact through multi-touch and/or tangible input objects. Tabletops are distinguished from many CSCL technologies in that they are intended for co-located face-to-face synchronous collaboration and they support multiple learners to interact simultaneously with a system through visible gestures and actions (Bruun *et al.*, 2017; Dillenbourg and Evans, 2011; Evans and Rick, 2014). The combination of social and physical characteristics of tabletops combined with the challenges of supporting productive group dynamics in collaborative learning also pertain to many other emerging mixed-reality platforms. Platforms that provide similar affordances (i.e. support for simultaneous group activity including shared inputs) can be used to facilitate collaborative interactions so it is important to understand how particular design strategies, decisions and features create conditions that enable desirable behaviors.

2.1. Interactional processes in CSCL

Collaborative learning is characterized by a 'mutuality of influence' among peers (O'Donnell and Hemlo-Silver, 2013, p. 2). Such bidirectional influence is commonly conceptualized as part of a collective convergent development of thinking toward a state of shared understanding (c.f. Tissenbaum *et al.*, 2017). The interactional processes of meaning-making through which such intersubjectivity can come to occur, and their productive mediation by designed artifacts, is thus a central focus for CSCL (Stahl and Hakkarainen, to appear). Two interactional processes identified as key contributors to collaborative learning are the giving of explanations and the joint resolution of conflict. Each provides a mechanism for learners to negotiate common ground (Beers *et al.*, 2007); that is, for learners to work toward a shared understanding of information, beliefs, assumptions and, in the case of sustainability, values (Clark and Brennan, 1991). The importance of the ongoing coordination efforts, such as explanation-giving and joint resolution of conflict, to generate and sustain communality is also consistent with Roschelle and Teasley's seminal definition of collaboration (Roschelle and Teasley, 1995).

Explanation-giving is core to many foundational models of interactive processes for collaborative learning. For example, a key element in creating effective argumentation is the process of using evidence and reasoning (Wise and Hsiao, 2019), that is explanation-giving, to justify one's position (Clark and Sampson, 2008). Explaining the reasons for one's claims offers a partner acess to how a learner is approaching a situation, the kind of information that is seen as relevant and the assumed values and goals a learner is trying to meet. As a collaborating learner engages in explanation-giving the opportunity arises for their partner (and themselves) to be open to other ways of thinking and perspectives. It is thus invaluable in the quest to negotiate common ground and measures of explanations (or warrants) for claims have been commonly used an indicators of argumentation quality in collaborative learning (e.g. Campbell *et al.*, 2020; Wise and Hsiao, 2019). Explanation-giving is also central to the notion of transactive discourse in CSCL (Stahl, 2013) in which a collaborator makes their reasoning visible to their partner and ties it to priors in the conversation. A display of reasoning is considered to include some sort of an evaluation, comparison or causal mechanism to justify a position (Fiacco and Rosé, 2018). Transactivity has been shown to be associated with learning in teams in naturalistic settings (Vogel *et al.*, 2016) as well as ones in which it was induced through design (Wen *et al.*, 2017). The mechanism here posits not only that making one's thinking visible through explanation-giving can help the learner partner to move closer in understanding, but also that it can lead the explainer to revise their own thinking as well. Thus, while it is optimal for explanation-giving to flow in both directions, even when only one learner provides an explanation, it can help the other and themselves see a new perspective, and play a part in the negotiation of common ground.

In an interactive tabletop type situation, learners' actions (e.g. gestures, interface touches, tangible object movements) can contribute to the giving of an explanation with or without concurrent verbalizations. Verbalizations and gestures focusing on objects may include descriptions or identifications of the objects, but may also serve more substantive roles in the collaborative task such as making a comparison or showing a causal logic. The tabletop system acts as a medium for this joint activity and thus its design may constrain or guide collaboration in various ways (Suthers, 2006; Tissenbaum *et al.*, 2017). Prior work with a tangible tabletop in a mixed-reality environment that prompted students to explain their reasoning observed that even when explanations were quite short, the cumulative effect was one of learning through explaining to each other (Yannier *et al.*, 2013). Explanation-giving, which includes a *why* as well as a *what* in the context of collaborativley solving a task, is a critical interactional process in negotiating common ground. We code and examine instances of the two constructs: *two-way explanations* (involving both learners) and *one-way explanations* (involving a single learner).

Another interactional process that supports the negotiation of common ground is the resolution of conflict: a recognized disagreement about ideas, opinions, goals or values (Beers *et al.*, 2006). Surfacing or creating socio-cognitive conflict is a common strategy in CSCL (Vogel *et al.*, 2017) where various scripts may induce learners to 'identify, discuss and resolve differences of opinion and knowledge' (Weinberger *et al.*, 2013). Conflict offers an important opportunity to negotiate common ground if it is resolved by the learners together (van Boxtel *et al.*, 2000), leading to a recognition of alternative perspectives, updates to personal and shared understandings and the building of more complex and meaningful knowledge structures (Schwarz and Asterhan, 2010). There may also be a benefit for explanation-giving (Woodward *et al.*, 2018) as learners try to convince one another. However, often consensus that is reached quickly and superficially or conflict that is resolved unilaterally by only one learner, misses an opportunity for negotiation and detracts from the establishment of common ground (Weinberger and Fischer, 2006). In mixed-reality environments that support social and/or embodied interaction, such as tabletops, conflict can also be expressed physically, for example by one learner dominating interaction with the table, blocking access to tangible or digital objects or taking actions that negate those taken by another learner (Jamil *et al.*, 2017; Marshall *et al.*, 2009; Woodward *et al.*, 2018).

The second focus of our analysis of children's interaction during the tabletop learning activity is on conflict resolution, since when this occurs jointly is an important contributor to negotiating common ground. We code and examine instances of the two constructs: *bilaterally resolved conflict* (in which learners work through their difference together) and *unilaterally resolved conflict* (where there is a failure to negotiate and one learner takes an un-agreed upon action).

In summary, based on our conceptualization of negotiation processes as critical to successful collaborative learning, our analysis of children's interaction during the learning activity focuses on explanation-giving and conflict. We code and examine instances of a total of four contructs: *two-way explanations* (involving both learners) and *one-way explanations* (involving single learner) as well as *bilaterally resolved conflict* and *unilaterally resolved conflict*. We compare instances of these four constructs both quantitatively and qualitatively between roles/no roles groups (design strategy for positive interdependence) and across groups (design strategy for reflective pauses). For reasons of scope, we do not examine the overlap of explanation-giving and conflict together.

2.2. Designing for positive interdependence

One approach to designing tangible tabletops that can support the negotiation of common ground is to structure positive interdependence into the activity design in using technical as well as physical and social design elements (Antle and Wise, 2013; Dillenbourg and Evans, 2011). Positive interdependence refers to the extent to which group members are dependent on each other for effective action (Johnson and Johnson, 1999). A classic example is the jigsaw script (Dillenbourg and Hong, 2008) where each person is given part of the information or expertise needed to be successful in the task, thus requiring people to work together to be successful. There are a variety of additional CSCL scripts designed to create positive interdependence in different ways, for example, via assignment of roles or designation of tools to particular learners (Järvelä *et al.*, 2004; Vogel *et al.*, to appear). The aim of creating positive interdependence is to encourage learners to work together in ways that require the negotiation of common ground as opposed to working independently, in parallel or in divide-and-conquer mode.

In the context of tangible tabletops Antle and Wise (2013) have suggested that positive interdependence may be achieved through a combination of technical and social system design. Physical objects, such as tangible input objects or networked augmented reality devices, offer particular affordances for creating positive interdependence as they allow for the physical embodiment of distributed control and can tap into social norms around object ownership and use (Speelpenning *et al.*, 2011). Such interdependence can be employed through physical means (e.g. using colors to designate tangible pieces for use by different group members; Dillenbourg and Evans, 2011) or in concert with social interdependence (i.e. tools are distributed in alignment with particular roles or duties). A combination of these strategies is particularly attractive as a way to address the challenge of getting learners to actually adopt the distinct rights and responsibilities of the role they are assigned (Wise *et al.*, 2012). The specifics of how we instantiated a design strategy for positive interdependence in Youtopia is described below in the context of our overall system design.

2.3. Designing for reflective pauses

Previous research with tangible tabletops has pointed to the need for design strategies that enable opportunities for joint reflection within collaborative interaction with tabletops (Antle, 2014; Okerlund *et al.*, 2016; Price *et al.*, 2010). This has been described as the need for both diving-in, through direct interaction with learning materials and space for stepping-out to co-construct deeper meanings collaboratively (Ackermann, 1996). In the context of tangible tabletops, Antle and Wise (2013) have suggested using the temporal and spatial properties of interaction to slow down actions and provide opportunities that trigger reflection. For example, in a fast-paced touch tabletop sustainability activity *world events* can be used to spark joint reflection; these are system events that pause interaction, take over the display and provide status information about the health of the world and in doing so provide a reason for students to reflect before they continue in their task (Antle, 2014). Based on this prior work, we suggest that *reflective pauses* are an important design strategy to ensure that throughout the activity students have breaks in interaction accompanied by reasons to reflect which may lead to rich negotiation-based dialogue. The specifics of how we instantiated design strategies for reflective pauses in Youtopia are described below in the context of our overall system design.

3. RESEARCH CONTEXT: YOUTOPIA

Youtopia is a collaborative tangible and multi-touch tabletop simulation that helps children learn about sustainable land-use planning. It was designed for pairs of elementary school learners and aligned with the environmental and sustainability topics in the Prescribed Learning Outcomes (Grade 5) and the National Science Education Standards (K-4) for students in British Columbia, Canada. Key learning goals included the following: recognizing that resources are things that we get from the living and non-living environment to meet the needs and wants of a population and that the supply of many resources is limited; describing how the use of particular resources contribute to meeting human needs and the environmental condition; and analyzing how people can demonstrate stewardship of resources and the environment that balance human and environmental needs. Using Youtopia, learners have the opportunity to design their own world, exploring how different land-use decisions affect the amount of food, housing and energy provided to the population and the impact these decisions have on the level of pollution in the environment. The primary mode of interaction is with land-use stamps, and other stamp tools (described below) (Fig. 2a). Using a simulation enables learners to explore the consequences of their actions in ways that are realistic in terms of sustainable land-use planning and understandable to learners in the target age group (Antle *et al.*, 2011).

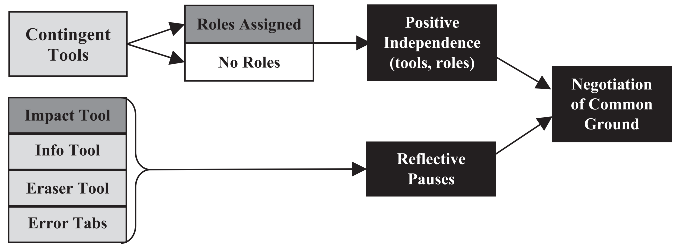


FIGURE 1. Tangible system features to enact design strategies for encouraging the negotiation of common ground; roles are human development and natural resource managers.

3.1. Design strategies, decisions and features

A design strategy is a commitment to an overarching approach to system creation. We then make design decisions in line with that strategy that result in specific system features. These features offer affordances for and constraints on interaction (with the tabletop system), which in turn create, shape and bind opportunities for collaborative learning interactions with other learners. We implemented two primary design strategies focused on support for collaborative learning: (i) positive interdependence and (ii) reflective pauses (see Fig. 1). We also followed general tangible design guidelines for supporting collaborative learning on tabletops (e.g. Antle, 2014), such as providing multiple ways of accessing and interacting with the tabletop (Olson *et al.*, 2010), and general recommendations for collaborative learning about value-laden topics, such as using value-neutral language, removing explicit end goals and enabling bi-directional exploration of the task (Antle *et al.*, 2014a, 2014b; Antle, 2014).

Our approach to designing for positive interdependence involved using a combination of social, physical and technical design elements. We set up a situation for positive interdependence by first creating a technical system involving tightly coupled (or contingent) inputs in the form of a set of tangible input tools. Tangible input tools provide access points that are sequences of inputs that must be taken in order to create a successful system response. Land uses (either natural resource or human development) are designated using a tangible stamp tool for a particular land-use type. Contingent tools are color coded by land-use type to help learners understand which stamps work together (e.g. Fig. 2b). To create shelter, food or energy land uses, at least one natural resource and one human development stamp for that land use must be used. For example, to create shelter, a learner must use the lumber stamp (natural resource) to designate trees to harvest before they can use the housing stamp (human development) to place any type of shelter on grassland. The goal of contingent tools was two-fold. First, it aimed to encourage learners to explore the relationships between different kinds of land-use activities (e.g. harvesting trees into lumber, which is then used to build housing, and which reduces forested areas available

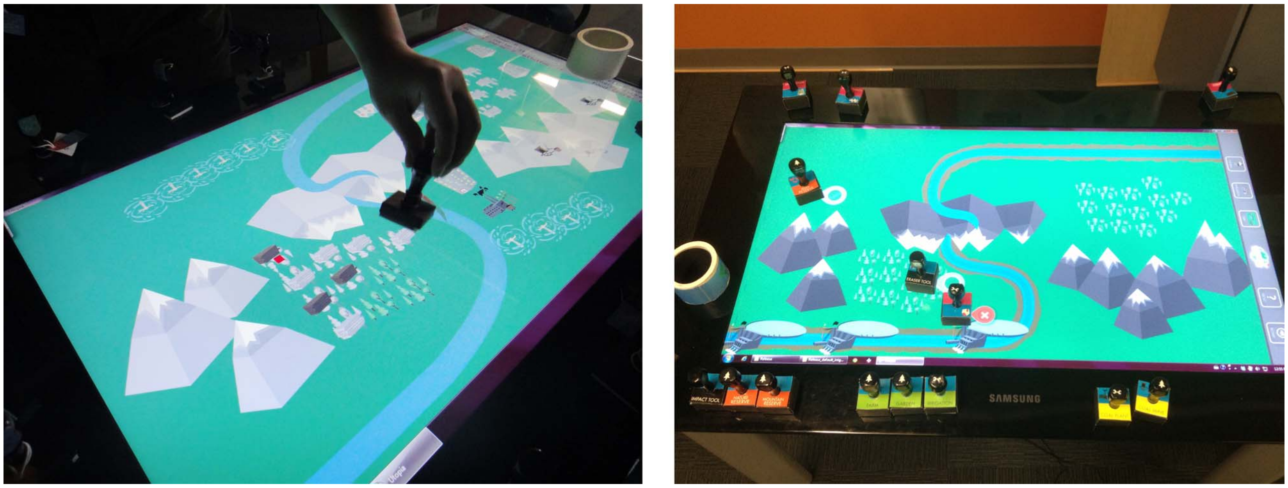


FIGURE 2. Youtopia (a) stamping to designate a land use and (b) colored tags identify groups of contingent (related) stamps to create shelter, food and energy.

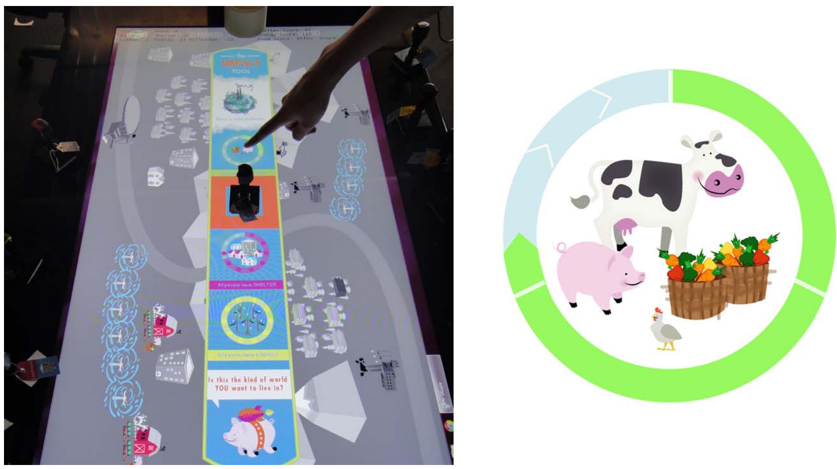


FIGURE 3. Youtopia (a) impact tool and world state overlay and (b) food impact ring.

for reserves). Second, the technological dependencies between the tools were intended to encourage positive interdependence among learners by requiring sequences of multiple inputs to create system responses. With only the contingent (technical) tool design, individual learners could feasibly enact a sequence on their own as well as with their partner. In order to strengthen our design for positive interdependence we added physical and social design elements to our system to support the enactment of roles. We marked the natural resources and human development tangible stamps with corresponding icons: a tree or wrench (physical design). This allowed us to use physical representations to layer social practices on top of the contingent tools by assigning learners in each pair to the role of a natural resource manager or human development manager and give them their subset of marked stamps (social design) (Fig. 1, top). While actual tool use is determined by the learners, prior work has shown social practices around object ownership often inhibit learners from taking tangible tools that were assigned to their partner (Fan *et al.*, 2014; Speelpenning *et al.*, 2011).

Four system features were designed with the goal of creating opportunities for *reflective pauses*, in which interaction with the technology is slowed to make room for reflection and discussion (Fig. 1, bottom). The first was the *impact tool*, a shared stamp, which enabled either learner to stop interaction and trigger an overlay status of the current world state (with respect to levels of shelter, food, energy and pollution) (Fig. 3). Learners could interact with the overlay display using touch to reveal the interrelations between the world's levels and the particular land uses in place. The second feature was the *information tool*, a ring into which any land-use stamp could be placed to stop system interaction and display the description,

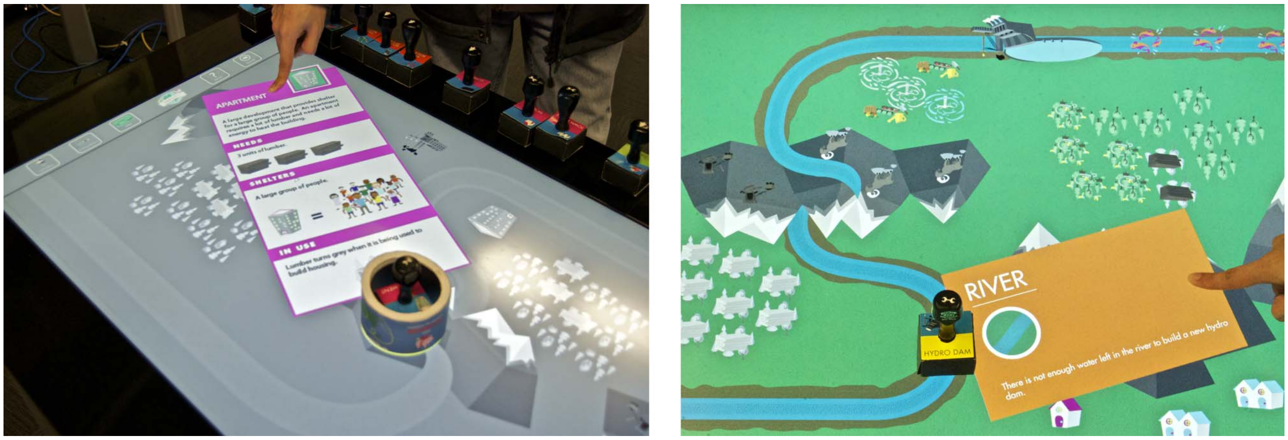
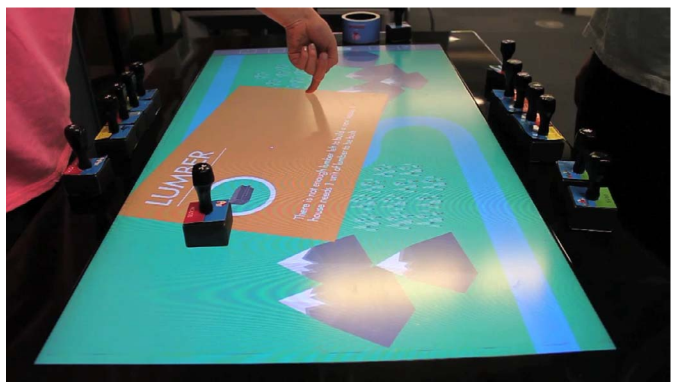


FIGURE 4. Youtopia (a) information tool card and (b) land-use error tab.

productivity, costs and benefits for the land use on a rotatable information card (Fig. 4a). The third feature was an *eraser tool*, a shared stamp, which could be stamped on top of land uses to undo them. The intent of this feature was to lower the barrier to try out actions and discuss their consequences; it also prevented one learner from permanently committing the pair to an action. While the eraser tool did not explicitly stop system interaction, the possibility to undo any action created the potential for an implicit pause after actions were taken to consider if they should be kept or undone. The fourth feature was *error tabs,* which were triggered when land-use stamps were placed in invalid locations (e.g. house in a river). The tabs paused interaction and if the learner touched the color-coded tab then another form of digital card (Fig. 4b) provided learners with information on why the location was incorrect, offering another opportunity to pause and reflect.

3.2. Usage scenario

A typical usage scenario begins with a pair of learners choosing one of four digital maps of an undeveloped valley with different types of terrain: mountains, grasslands, forest and a river. The primary method of interaction with the tabletop is through the land-use stamps, which have predefined relationships to each other and to the terrain designed to reflect real-world relations (Table 1). For example, a farm can only be built on grasslands (not on a mountain) and requires irrigation connecting it to a water source (the river). Thus, as described above, different inputs to Youtopia are contingent and learners can learn about these relationships through the information tool and the error tabs (Fig. 4). When a learner stamps a 'legal' land use (in an allowed location; required resources are met), a digital version of the land-use picture on the stamp appears on the map and any required resources it uses are grayed out. Learners can use the impact stamp to assess the state of their world in terms of what proportion of the population has shelter, food and energy, as well as how polluted the world is. Learners can touch the shelter, food, energy or pollution rings to see the associated land uses light up on the map (Fig. 3). On the impact overlay the pig asks 'Is this a world you want to live in?' with the goal of eliciting discussion. Youtopia was implemented on a Microsoft PixelSense digital tabletop. Usability testing to ensure basic standards were met was conducted prior to running the study. A short video of Youtopia's functionality can be viewed through link at Video 1.



VIDEO 1. Functionality of Youtopia system tabletop [Go to https://vimeo.com/376547547].

4. RESEARCH DESIGN AND QUESTIONS

In this paper we report on our evaluation of the effects of two different levels of positive interdependence (contingent tools only and also assigning learners roles and physically marked associated controls) and the four reflective pause features (info tool, impact tool, eraser tool, error tabs) on collaborative activity. We used a explanatory mixed methods approach (Creswell and Clark, 2011) with an experimental manipulation

TABLE 1. Types of land-use stamps.

Area of human need	Natural resource stamps		Human development stamps
Food (green labels)	Garden, farm	⟵	Irrigation
Shelter (pink labels)	Harvest lumber	⟶	Houses, town houses, apartments
Energy (yellow labels)[a]	Coal mine	⟶	Coal plant, hydro plant
Environment (orange labels)[b]	Forest, river and mountain reserves		

Arrows indicate which land uses create resources required for other land uses.
[a]Energy land uses increase the pollution in the world to different extents.
[b]Environment land uses reduce the pollution in the world to different extents.

of the level of positive interdependence (roles/no roles) in which the initial quantitative analysis of the data identified the relevant video segments for subsequent qualitative analysis (Paulus and Wise, 2019). We examined the effects of reflective pauses on both conditions, as prior work has shown that it is important as a means to create opportunities for reflection and dialogue-based negotiation. The study took place in an authentic school environment, addressing critiques that interactive tabletop research has been overly focused on tool development rather than in vivo studies of collaborative learning (Higgins *et al.*, 2011).

Phase 1 of the study used a quantitative analysis of the data to examine and compare collaborative processes and understand the impact of our approach to supporting positive interdependence (via roles) on these processes. Two research questions probed the *process* of learners' collaboration along three dimensions. These were the most direct measure of the effects of our design strategies on collaboration, thus our primary area of investigation.

RQ1: To what extent do learners using the Youtopia tangible tabletop sustainability simulation engage in the following collaborative processes?

1. Working together
2. One-way or two-way explanations
3. Resolving conflicts unilaterally (one-way) or bilaterally (two-way)

RQ2: Does assigning learners roles with associated tangible controls in Youtopia increase the extent to which learners engage in these processes?

We also asked two research questions that examined the *outcomes* of learners' collaboration along two dimensions. This was an important, but more distal measure of the impact of our design strategies on collaboration, since multiple factors can impact learning outcomes.

RQ3: To what extent do learners who have used Youtopia display evidence of the following learning outcomes?

1. Understand the complexity of making land-use decisions
2. Value land-use decisions that balance meeting human and natural needs

RQ4: Does assigning learners roles with associated tangible controls in Youtopia increase the extent to which they display evidence of these outcomes?

Phase 2 of the study used a qualitative analysis of the explanation and conflict events identified in the quantitative analysis to better understand the nature of the interactional processes that occurred and the relationship of these processes to design features.

RQ5: How were specific tools/tool features in Youtopia taken up by learners as part of collaborative processes P1, P2 and P3 (see above)?

RQ6: How did assigning learners roles with associated tangible controls impact the ways specific tools/tool features in Youtopia were taken up by learners as part of collaborative processes P1, P2 and P3 (see above)?

5. OVERALL METHODS

5.1. Participants and learning environment

Forty fifth grade learners (age: 10–11 years; 18 boys, 22 girls) from two classrooms participated in the study in pairs ($N = 20$) assigned by the teachers to match learners based on three criteria: (i) learners work well together; (ii) learners of high ability are distributed across pairs; and (iii) pairs do not have one individual who is verbally dominant over the other. In addition, teachers were asked to make mixed-gender pairings; however, the class gender ratio necessitated one girl–girl pair in each class. Pairs were randomly assigned (by the researchers) to the roles or no-roles condition, with the restriction of equal representation in each condition across the two classes. Learners were mostly regular users of technology, though there were some exceptions. Due to the culture of the classrooms (and overall school) all learners had extensive prior experience collaborating. In addition, all learners had participated in a class unit on sustainability issues four months earlier, thus prior knowledge on the topic was generally high. Youtopia was introduced as a review of the sustainability unit in which learners would have the opportunity to create a world they would want to live in then share and explain it with the class. Because collaborative activity was our focus (and we expected learning partners to influence each other) pairs of learners were taken as the unit of analysis.

5.2. Data collection

The primary source of data was *video*. Two installations of Youtopia (tabletop system, tangible objects and associated software) were set up apart from the regular classroom to create a distraction-free environment. Each room was equipped with a high-definition digital video camera capturing a landscape view of the learners (and an oblique view of the tabletop). Videos of 20 sessions of approximately a half-hour each were collected.

Data was collected using a *questionnaire* for learners. At the end of their time using Youtopia, learners were given a closed-ended questionnaire that was delivered verbally and audio recorded. The questionnaire asked for the following: demographic information (age and gender); the frequency with which they used various technologies at home (two questions); their self-reports of the process of working and talking with their partner (four questions); and what they learned about making land-use decisions (four questions). Full question text is included in the results section. For each question, learners indicated whether a statement was true/important/difficult on a five-point scale ranging from 'not at all' to 'very.'

Data was also collected through *teacher evaluations* of final world presentations.

After all learners had completed their Youtopia sessions, each pair presented a printed-out version of their final world map and impact display to the rest of their class explaining:

- The world they created, the rationale for their choices and the trade-offs that were made
- Why they did or did not want to live the world they created

They were also asked to reflect on the following:

- The benefits of working together
- The challenges of working together
- If the world they created reflected what both members of the pair thought was important in balancing human and natural needs

Each classroom teacher evaluated whether learners met, approached or did not meet expectations on each of these five elements using a five-point scale (5 is high). However, in practice the range of this scale was severely restricted as teachers never assigned a score of '1' or '2' for any of the criteria and only assigned a '3' on rare occasions.

5.3. Procedure

Three research team members administered each session of Youtopia; classroom teachers were not present. Pairs were told they would have up to 25 minutes to engage in the activity. The facilitator began by introducing the learners to Youtopia and showing them the basic tutorial of system functionality. Learners were then invited to use Youtopia to create a 'world they would want to live in' that they would later share with the rest of their class and teacher. Specifically, they were told to work together to make shelter, food, energy and nature reserves and that they could change and rebuild their world until they were happy with it. No instructions were given as to what the created world should look like.

In the roles condition, one learner was assigned to be the 'natural resources manager' and given all the 'tree' stamps associated with this role (lumber, garden, farm, coal mine, forest reserve, river reserve, mountain reserve); the other learner was assigned to be the 'human development manager' and given the 'wrench' stamps associated with this role (irrigation, house, townhouse, apartment, coal plant, hydro dam). Roles were assigned randomly to learners by the researchers, balancing across gender in the overall sample. Tools not associated with a particular role (impact tool, information tool, eraser tool) were placed at the end of table between the learners. In the no-roles condition the pair was simply given access to all of the stamps/tools placed at the end of the table equidistant between them and grouped by color related to particular human needs (Table 1 and Fig. 2b). Youtopia activity sessions were spread across the course of a week.

6. PHASE 1: QUANTITATIVE ANALYSIS AND RESULTS

6.1. Data coding

Video data was coded to index two aspects of learners' collaborative processes: first, the degree and type of their *explanations* (*one-way/two-way)* about the sustainability domain; and second, the degree of *conflict* they had around the sustainability domain and how it was resolved (*unilaterally/bilaterally*). We had initially also planned to code a more general collaboration measure of 'working together' (time in which both learners worked on a common element of the task); however, since all pairs in the study were seen to work together all the time, this measure was discarded and working together was indexed simply by the total time the learners engaged with Youtopia.

Explanation Events were periods of Youtopia use in which one or both learners explained their thinking or reasoning related to decisions about what resources and developments to use in the activity, and in which they inferred or made mention of one or more values in that explanation. For example 'Let's build houses, not apartments - they use less lumber so we can make more forest reserves' would be coded as a one-way explanation. However, the statement, 'I think we should have houses not trees' would not be coded as an explanation event because it lacks a 'why' or 'because' reason in addition to the 'what.' While individually such sentences

TABLE 2. Working together variables by condition.

	No roles (N = 10)	Roles (N = 9)	t	P [b]
‘I worked a lot with my partner while I was doing the activity.’[a]	4.35 (0.41)	4.28 (0.36)	−0.40	(0.336)
‘I worked mostly on my own while I was doing the activity.’[a]	1.48 (0.45)	1.56 (0.52)	0.36	(0.361)
Duration of system use (min)	21.85 (4.55)	24.99 (3.43)	1.69	0.055
Challenges of working together discussed in presentation (teacher scored)	4.50 (0.85)	4.11 (1.1)	−0.88	(0.197)
Benefits of working together discussed in presentation (teacher scored)	5.00 (0.00)	4.33 (1.0)	−2.00	(0.040)

[a]Survey scale ran 1–5; higher numbers indicate greater level of agreement.
[b]P values given are for one-tailed tests; parentheses indicate if difference was not in predicted direction.

may not seem as in-depth as educators might aspire for, the inclusion of (any) justification is noteworthy for this population (ten year olds) and the accumulation of such statements over time could position reasoned, values-based decision-making centrally in their collaborative dialogue. Occasions in which only one learner explained their thinking or reasoning were coded as *one-way explanations*, while episodes in which both learners explained their thinking were coded as *two-way explanations*.

Unilaterally/Bilaterally Resolved Conflict Events were periods of Youtopia use in which learners expressed verbal and/or physical disagreement with the other’s actions or utterances related to the sustainability domain. For example, if one learner started to stamp a Garden and the other said ‘No, let’s make a Farm,’ or one learner wordlessly grabbed another’s stamp it would be coded as conflict. However, if one learner presented options and the other decided, (e.g. ‘We could make a Garden or a Farm . . . ’ ‘Farm!’) it was not considered conflict. Each conflict event was coded for whether it was *unilaterally resolved* (a learner took final action without other’s consent) or *bilaterally resolved* (agreement was reached before final action was taken).

Three researchers were involved in coding the video data, marking all *one-way/two-way explanation* and *unilaterally/bilaterally resolved conflict* events of the types described above with both a start and end time. These were used to calculate variables for both the frequency (number of occurrences) and average duration of each kind of event. Because the presence or absence of assigned roles was apparent in the videos, coders were not blind to condition. Coders trained on a practice video prior to actual coding. Inter-rater reliability was calculated using Cohen’s kappa based on the overlap of time segments coded permitting a 5-second tolerance at the start and end of events. Thirty percent (six) of the videos were double coded, three at the start of the analysis ($\kappa_{\text{Explanation}}$ = .63; κ_{Conflict} = .81), and three at the midpoint ($\kappa_{\text{Explanation}}$ = .65; κ_{Conflict} = .92). All differences in coding were reconciled.

6.2. Results

Youtopia gameplay sessions lasted 14–30 minutes, with an average length of 23 minutes (SD = 4.4). There was one outlier pair (roles condition) with no explanation or conflict events of any kind; video review showed the pair to be quiet and disengaged from the task throughout the session, thus the pair was excluded from further analysis. For the remaining 19 pairs, data is presented by measure first descriptively across the entire sample (RQ1 and RQ3), followed by a comparison across role/no-role conditions (RQ2 and RQ4). For comparisons, due to the small sample size and a clearly identified hypothesized direction of effects, one-tailed tests were used.

P1: Working together.

All pairs reported high levels of working together; no differences were seen between the two conditions (see Table 2). The amount of time actually spent working together (indexed by duration of Youtopia use) was 3-minute longer on average for pairs in the roles condition; however, the difference failed to reach significance. There was no difference in the teachers’ evaluation of the degree to which learners discussed the challenges they encountered in working together. However, the evaluation of the degree to which they discussed the benefits of working together in their class presentation was somewhat higher for the no-roles condition; had our hypothesis been in the opposite direction, this result would have been significant.

P2: Explanations (one way/two way).

The total number of explanations per pair ranged between 2 and 19, with an average of 10 per session, accounting for ~5% of learners’ total play time. Looking at patterns of explanations across all pairs, on average there was a greater frequency of one-way explanations (M = 7.26, SD = 3.90) than two-way explanations (M = 2.95, SD = 2.32) [$t_{18} = 6.31$, $P < .001$]. However, when they occurred, two-way explanations had longer average durations (M = 10.37 sec, SD = 4.37) than one-way explanations (M = 4.33 sec, SD = 1.09) [$t_{16} = 5.39$, $P < .001$]. Comparing role and no-role conditions, the number, but not length of one-way explanations was greater for pairs in the roles condition; however, no differences were seen in the number or length of two-way explanations (see Table 3).

P3: Engaging in and resolving conflict.

The data distribution for conflict was heavily skewed and kurtotic due to a substantial number of pairs without any events; thus assumptions of normality were violated and non-parametric tests used. The predicted higher frequency of unilaterally resolved conflict for the no-roles condition was observed

TABLE 3. Frequency and length of explanations by condition.

	No roles (N = 10)	Roles (N = 9)	t	P [a]
	Mean and standard deviation			
One-way explanation				
Frequency (number)	5.80 (2.86)	8.89 (4.40)	1.83	0.042
Average length (sec)	4.35 (1.05)	4.37 (1.12)	0.06	0.957
Two-way explanation				
Frequency (number)	2.60 (2.12)	3.33 (2.60)	0.68	0.254
Average length (sec)	10.89 (5.14)[b]	9.78 (3.58)[b]	0.51	(0.619)

[a] P values given are for one-tailed tests; parentheses indicate if the difference was not in the predicted direction.
[b] N in this cell was reduced by one, after removing a pair that did not have any two-way explanations.

TABLE 4. Frequency and duration of conflict types by condition.

	No roles (N = 10)		Roles (N = 9)		Mann–Whitney P
	Median	Max	Median	Max	(One-tailed)
Unilaterally resolved conflict					
Frequency (number)	0.5	4	0	1	0.030
Average duration (sec)	6.67[a]	12.5	4.4[b]	4.4	-
Bilaterally resolved conflict					
Frequency (number)	1	8	0	3	(0.029)
Average duration (sec)	9.32[c]	22.7	32.73[d]	50.5	0.031

[a] $N = 5$.
[b] $N = 1$.
[c] $N = 8$.
[d] $N = 4$.
Mann–Whitney test was not run if combined N across cells <10.

(see Table 4). However, results unexpectedly showed the no-roles condition also had a greater frequency of bilaterally resolved conflict; had our hypothesis been in the opposite direction, the difference would have been significant. When bilaterally resolved conflict did occur for roles pairs, it lasted significantly longer than bilaterally resolved conflict for no-roles pairs. As there was only one instance of unilaterally resolved conflict in all the roles pairs, it was not possible to meaningfully compare duration.

O1: Understanding the complexity of making land-use decisions

Overall learners reported moderate levels of understanding of the complexity of making land-use decisions (Table 5). No differences between conditions were found. The teachers' evaluations of the content of learner presentations was consistently high, with all pairs receiving a 5 on one of the two criteria and only two pairs receiving a 4 instead of 5 on the other, thus no significant differences were found.

O2: Valuing land-use decisions that balance meeting human and natural needs

After playing with Youtopia, all learners reported generally high levels for the value they placed on making land-use decisions that balance human and natural needs. These values were somewhat higher for the no-roles condition; had our hypothesis been in the opposite direction, this result would have been significant (Table 6). A similar trend was seen in learners' reports of having learned about balancing needs by working with their partner and the teachers' evaluations of learner descriptions of how they balanced what each team member thought was important.

7. PHASE 2: FOLLOW-UP QUALITATIVE ANALYSIS AND FINDINGS

The quantitative analysis revealed significant differences between role and no-role conditions in the frequency of one-way explanations as well as in the frequency of unilaterally resolved conflicts and both frequency and duration of bilaterally resolved conflicts. To examine how and why these differences occurred as well as probe the ways in which our design strategies of positive interdependence and reflective pauses supported explanations and conflict events, we conducted a follow-up qualitative analysis of the video data (Creswell and Clark, 2011). Specifically, we explored the general character

TABLE 5. Understanding complexity of land use variables by condition.

	No roles (N = 10)	Roles (N = 9)	t	P [b]
	Mean and std. dev.			
'Making land use decisions that balance natural and human needs is difficult.'[a]	3.15 (0.58)	2.92 (0.81)	−0.73	(0.239)
'Everyone should have the same idea about the kind of world they want to live in.'[a]	2.70 (0.75)	2.72 (0.51)	0.08	0.470
Clear description of how did/did not want to live in their Youtopias world (teacher scored)	5.00 (0.00)	5.00 (0.00)	-	-
Rationale given for decisions/tradeoffs (teacher scored)	5.00 (0.00)	4.78 (0.44)	−1.51	(0.085)

[a]Survey scale ran 1–5; higher numbers indicate greater level of agreement.
[b]P values given are for one-tailed tests; parentheses indicate if difference was not in predicted direction

TABLE 6. Mean and standard deviation of valuing balance in land-use variables by condition.

	No roles (N = 10)	Roles (N = 9)	t	P [b]
'Making land use decisions that balance natural and human needs is important.'[a]	4.65 (0.34)	4.36 (0.28)	−2.01	(0.031)
'Working with my partner helped me learn about balancing human and natural needs.'[a]	3.90 (0.81)	3.44 (0.53)	−1.43	(0.085)
Described if world reflected what each member thought was important in balancing human and natural needs (teacher scored)	4.90 (0.32)	4.44 (0.73)	−1.74	(0.055)

[a]The survey scale ran 1–5, with a higher number indicating a greater level of agreement with the statement.
[b]P values given are for one-tailed tests; parentheses indicate if the difference was not in the predicted direction.

of how each of these interactions were taking place across both conditions (RQ5) as well as the ways they were taking place differentially in the roles and no-roles conditions (RQ6). Our goal was to draw threads of connection between the instantiated design strategies of positive interdependence and reflective pauses and how collaborative processes were enacted in Youtopia. As two-way explanations were relatively few in number and did not differ across conditions, they were not examined. Particular attention was paid to the concerns of video-based data (Derry *et al.*, 2010) in terms of clip selection (using the events identified in the quantiative analysis as the sample) and support for pattern finding (using a combination of transcription and narrative summary). Data analysis was conducted inductively following the constant comparative method (Auerbach and Silverstein, 2003; Gibson and Brown, 2009), an approach in which researchers systematically compare each new unit of data (e.g. a segment of video in which an explanation takes place) with all previous units as well as any commonalities across data units that have already been identified. The goal is to identify themes of meaning, where importance derives not simply from the number of times something occurs, but also its weight and apparent consequence to participants. Standards for rigor in this tradition differ from traditional notions of independent inter-rater reliability and instead refer to credibility (the extent to which findings offer a valid representation of reality) and dependebility (the consistency and repeatability of findings) (Lincoln and Guba, 1985). This study established credibility through triangulation (ensuring data from multiple sources—participants, times, areas of focus—supported each finding) and structural corroboration (checking all possible findings for disconfirming evidence and possible alternative explanations). Dependability was established through the application of a meticulous analysis processes (described below) and keeping an audit trail of all codes and decisions made at each stage in the process.

7.1. Analysis process

The video segments identified for each of the three categories in the original coding were transcribed by a researcher into a text file (Fig. 5). Transcriptions included (i) all verbalizations during the coded time period and two to four turns of talk before and after for context and (ii) indication of the physical actions taking place during/between turns of talk: (a) body position, (b) tool use, (c) gestures, (d) facial expressions and (e) learner location around the table. In addition, the transcriber provided a global overview of each event to provide context for reading the transcript.

Three researchers then individually worked in a sequential manner through the transcripts organized into sets by event-type and condition (e.g. one-way explanations in roles

L1 (f) Human Devel.	L2 (m) Natural Resour.	Verbalizations and Physical Actions Surrounding L1 Explanation in R1@8:39[1]
X	X	Both L1 and L2 place coal mine in info ring and read, mumbling to themselves.
	X	Oh so maybe it's already run out. That was fast [removes mine stamp and info tool from screen]
X		But we already put one [pointing to mountain area of map] coal mine thingy
	X	Let's try another one [stamps coal mine on mountain]
X		It might pollute a lot though [hovers coal plant stamp tentatively over mountain]
	X	Yea that's true
X		Let's try another reserve [puts coal plant down and erases the coal mine]

FIGURE 5. Sample transcript of a one-way explanation by learner L1 about her reason to stamp coal plant in roles pair R1 at 8 minutes and 39 seconds into the session.

condition)[1] to identify possible themes in the data using the constant comparative method (systematically comparing each new video segment with all previous segments of the same type and condition). Each possible theme found in a subsequent event-type/condition set was taken back for examination in all prior sets. The three researchers discussed all proto-themes by event type and condition, condensing and combining similar ideas. Each potential theme was then subject to individual scrutiny with a search through the transcripts for confirming/disconfirming evidence and any possible alternative explanations. Several themes were discarded for lack of sufficient substantiating evidence or relevance to the focus of the study while others were combined as overlaps were identified. In the end, the final set of consolidated themes with supporting evidence contained six themes related to explanation-giving and three relating to conflict.

7.2. Findings: one-way explanations

The six themes described below and summarized in Table 7 speak to how one-way explanations were initiated by learners using Youtopia, noting distinctions in how this happened with and without the assignment of roles/tools, and any ways the four *reflective pause* tools (i.e. impact, information, eraser tools and error tabs) were used within the context of explanation-giving for both groups.

Explanation Theme 1: Explanations Occurred as Responses to Different Things

One-way explanations in both conditions occurred commonly as a response to the world-state; in the roles condition explanations also occurred in response to a partner action or comment. In no-roles pairs, one-way explanations were commonly made in response to the state of the world. This was usually prompted by use of the impact tool, which paused interaction, and the feedback this tool provided, which promoted reflection (e.g. 'So how are we turning out [puts impact tool on screen]. Food is pretty good. I think it is really good because there is no pollution' L1 in N8@15:58). Learners also gave explanations of their thinking about the world state as depicted on the map (e.g. 'I don't like how we took up all the trees but [rubs hands on face] . . . like . . . I think it's good.' L1 in N1@18:03). Importantly, the explanation was given in direct response to the world-state information provided by Youtopia (map or impact tool). In **Roles** pairs one-way explanations were made in response to both the state of the world and directly to things the partner did or said (i.e. not the state of the world itself but the action the partner wanted to take on it). This second type of explanation often related to stamp ownership (e.g. 'Yea, because then most people will have food' L2 in R6@18:54 responding to their partner, who had the garden stamp but had not yet used it, making a hesitating statement that only 'maybe' stamping it was a good idea). Similar explanations occurred even when the action involved the eraser tool, which both learners had access to, indicating a tacit acknowledgement of the ownership of particular land-use decisions (e.g. 'These ones? [motioning to apartments] maybe we ∗should∗ lose some apartments. They're too cramped up in that area' L2 in R5@16:19, responding to their partner's suggestion that they should remove some of the apartments).

Explanation Theme 2: Temporality of Explanations: Backward Versus Forward looking

One-way explanations in both conditions were commonly retrospective reflections looking back on the state of the world; in the roles condition, explanations were also forwards-looking made as part of prospective statements about what should be done to change it. In **No-roles** pairs, one-way explanations were made as retrospective reflections (on the existing state of the world triggered by the impact tool as described above) (e.g. 'Wait, if you look at our pollution. See now our pollution is fine' L1 in N3@18:55). At times these also concluded with a call to action about what should be done in response or involved statements of a timeless nature describing what learners valued in the world (e.g. 'There should be at least many [people who have food]' L2 in N2@8:57) or ones which described an anticipated future (e.g. 'Yeah, it will be nice to have some animals' L2 in N6@3:21). In **Roles** pairs, there was strong presence of one-way explanations given as part of prospective calls-to-action. These occurred both in combination with reflections on the existing world-state triggered by the impact tool (e.g. 'Oh man, a lot of the water's gone [looking at the brown river], do you think we need to kill the hydro dam? L1 in R8@12:56') but also independently, which was not seen for no-roles pairs (e.g. 'I don't know about using coal because we don't want to make it too polluted' L2 in R3@10:20).

1 Because there was only one instance of unilateral conflict for the roles condition, no thematic analysis could be performed. Instead, this one incident was examined for the presence/absence of themes found elsewhere.

TABLE 7. Summary of one-way explanation themes.

#	Topic of theme	No roles only	Both groups	Roles only
1	Explanations as responses to things	N/A	Explanations as responses to world state	Explanations as responses to an action or comment made by the partner
2	Temporality of explanations	N/A	Backwards looking (explaining things that have already happened)	Forwards looking (explaining things that will happen in the future if a certain action is taken)
3	Collectivist vs. partner-oriented personal pronouns	N/A	Strong use of 'we' language	'We' language connected with direct references to the partner ('you')
4	Valence of language	N/A	Positive, explaining how world needs have been met	Negative/questioning, explaining how world needs are not yet met
5	Positionality of perspectives	Balanced human or environmental needs, either from start or by end	N/A	From human or environmental perspective the whole time or from both perspectives, then balanced
6	Stepping inside the world	N/A	N/A	Explanations included perspective of the world habitants

Explanation Theme 3: Collectivist Versus Partner-Oriented Personal Pronouns Used in Explanations

One-way explanations in both conditions involved strong use of collectivist language ('we'); in the roles condition language connecting this to the learning partner ('you') was also seen. In **No-roles** pairs, one-way explanations commonly involved use of first person plural (e.g. 'Okay so that means <u>we</u> need more trees which is kind of sad' L1 in N1@3:30) though some use of first person singular was also seen (e.g. '<u>I</u> think it is really good because there is no pollution' L1 in N8@13:05). When employed, use of the first person singular was almost always followed by an opinion verb such as think or feel (as in the example above) and often also connected with a reference to the collective (e.g. 'I feel like we're using up too much of the trees' L2 in N4@9:55). A similar pattern was seen for **Roles** pairs with the addition of notable use of the second person singular ('you') in combination with a reference to the collective (e.g. 'Do <u>you</u> want to try another irrigation to get more food 'cause that's the only way big problem <u>we</u> have?' L2 in R1@25:00).

Explanation Theme 4: Valence of Language Used in Addressing World Needs

One-way explanations in both conditions used positive language to give confirmation of needs being met; in the roles condition explanations were also given in response to unmet needs, either through negating things a partner had said/done or using questions to seek confirmation, agreement or action. In **No-roles** pairs, learners gave one-way explanations about three main aspects of the world (triggered by the impact tool display of world state) largely using positive terms: when the environment was relatively healthy (e.g. 'Okay there's little pollution. That's way better.' L2 in N1@7:25); when human needs were met (e.g. 'Oh wow . . . [pointing to full shelter indicator on impact display] . . . that's good!' L1 in N7@8:14) and in reference to the balance between the two (e.g. 'Well I want everyone to have energy but then we might have more pollution' L2 in N2@16:42). In a limited number of instances, no-roles learners did use negative terms; but these tended to be tied directly to action-oriented phrases about what should be changed. In contrast, in **Roles** pairs, learners gave their one-way explanations using a variety of neutral, positive and negative statements as well as questions. The presence of explanations with a negative valence was notable; learners often offered an explanation as they opposed something their partner had just said or done that had an undesirable impact on human needs or the environment (e.g. 'But this like pollutes though, remember?' L2 in R2@12:43 responding to their partner stamping a coal plant on the map). Often these opposing statements suggested undoing what the other learner had just done using the eraser tool (e.g. 'Maybe, ugh . . . Water brown?' [erases the irrigation they have just stamped in response to their partner's suggestion that they build more gardens and a farm] 'I don't want to do that 'cause then the fish don't have much water.' L2 in R5 15:02). Opposition was also enacted in the form of a question which opened up a space for the partner to share their thoughts in response to the difference in opinion (e.g. 'Why is the garden so far from the houses?' L2 in R2@3:14 [in response to L1 placing an apartment stamp]).' Roles pairs also sought confirmation, agreement or action from their partner either directly or indirectly before taking an action (e.g. '[placing impact tool] Not everyone has shelter . . . Do you want to take out some parks?' L1 in R8@8:48).

Explanation Theme 5: Positionality of Perspective in Explanations

Learners in the no-roles condition gave one-way explanations from a balanced perspective throughout the session or by the end; learners in the roles condition either gave explanations from the perspective of their role throughout the session or began from both perspectives, adopting a balanced perspective by the end. In **No-roles** pairs, learners generally gave one-way explanations concerning trade-offs and advocated for a balanced world at some point during their session. Some started like this from the beginning; others initially advocated for either people's needs or the environment, shifting to consider balance only later in the session (e.g. 'All I wanna do is add more energy but then that's gonna add more pollution' L2 in N2@20:08). In contrast, many learners in the **Roles** pairs advocated according to their assigned role for most of the session. As described in the prior themes, these explanations were often phrased in the negative and oriented toward taking action. For example, the natural resources manager gave one-way explanations when the impact tool display showed that pollution was high or water levels were low (e.g. 'Oh no no no no, we don't need that happening [used eraser tool to remove irrigation] we need to preserve some water [stamps a river reserve, water turns brown again, uses eraser tool to remove the reserve] that's not good.' L2 in R5@15:31) while the human development manager gave explanations when human needs were not met. However, in some pairs, learners gave explanations that were both aligned and in contrast with their assigned role. Near the end of their session, they then shifted away from the roles to address questions of balance, reflecting on the world state reflected in impact tool display and making comments that showed a recognition of the trade-offs involved (e.g. 'Now there's a little pollution but I think we're almost at full energy' L2 [natural resource manager] in R7@16:14).

Explanation Theme 6: Stepping Inside the World to Explain

Learners in the roles condition gave one-way explanations that included the perspective of the world's habitants. An additional theme found in the examination of one-way explanations in ***Roles*** pairs was comments about the experiences or feelings of the habitants of the world. There were a substantial number of these statements relating to a variety of things such as living conditions (e.g. 'Oh, they're neighbours [smiles]' L1 in R5@5:17, the availability and proximity to food (e.g. 'But should we do like houses around the garden? So they stay alive with food and stuff . . . ' L2 in R2@4:28), the impact of pollution (e.g. 'Do you want to put this over there so these people don't have like the pollution from that?' L1 in R1@20:51) and lifestyle concerns (e.g. 'I think we should make a few because people like nature reserves don't they?' L1 in R7@5:08). These comments all indicate thinking about or from the perspective of the people living inside the Youtopia world. Such comments were not seen as a theme in the ***No-roles*** condition where the vast majority of one-way explanations came from a detached 'god's-eye' view (e.g. 'Okay, there's little pollution. That's way better' L2 in N1@7:23).

7.3. Findings: engaging in and resolving conflict

The three themes described below and summarized in Table 8 speak to how conflict occurred and was resolved by the learners while using Youtopia with and without the assignment of roles/tools, and any ways the four *reflective pause* tools (i.e. impact, information, eraser tools and error tabs) were used within the context of conflict resolution for both groups.

Conflict Theme 1: Timing and Topic of Conflict

In the no-roles condition, unilaterally resolved conflict often occurred during action and revolved around competing uses of the same resource. In both conditions, bilaterally resolved conflict tended to occur prior to action and revolved around strategic choices and planning. **No-roles** pairs engaged in unilaterally resolved conflicts around competing uses of the same resource on the map (e.g. river, trees, mountains). Almost all of the unilaterally resolved conflict that occurred was triggered by each learner having a different desire for the use of the same resource for a development need or a reserve that would combat pollution. This type of conflict often occurred during action in response to one learner using a stamp to add or the eraser tool to remove a specific land use. For example, there was unilaterally resolved conflict about if trees should be used for lumber or forest reserves; if mountains should be used for coal energy or mountain reserves; and if the river should be irrigated or designated as a river reserve (e.g. L1 is working on food and says, 'Okay another one' and picks up irrigation stamp and moves toward river. L2 'Oh wait, no. I have an idea . . . cuz then . . . ' and stamps a river reserve on river. N7@16:29). There were a smaller number of conflicts of a more strategic nature that addressed the question of whether it was better to combat pollution with a forest or a mountain reserve. As there was only one instance of unilaterally resolved conflict across all roles pairs, this theme was not observed.

When ***No-Roles*** pairs engaged in bilaterally resolved conflict it was often about which kind of a specific land use to use (e.g. creating shelter with houses or townhouses, creating energy with a hydro dam or coal plant). No-roles pairs also engaged in bilaterally resolved conflict about making strategic rather than specific trade-offs about which resources to use to meet human needs while minimizing pollution (e.g. L2 has just erased a mountain reserve. L1 says 'We'll just add one more nature reserve.' L2 says, 'No'. L1 says, 'Just one because . . . ' L2 cuts L1 off and says, 'There's so much population. There'll be people sitting on the streets. Let's build a house or an apartment.' L1 picks up lumber stamp and says, 'okay do you want me to get rid of . . . ' and converts trees to lumber (rather than a forest reserve) N2@15:00). This type of conflict was often prior to one or both learners taking an action. This type of conflict *prior to action* often included the use of the impact and information tools as part of interaction. ***Roles*** pairs bilateral

TABLE 8. Summary of conflict themes.

#	Topic of theme	No roles only	Both conditions	Roles only
1	Timing and topic of conflict	Unilateral conflict occurred during action-taking and was about competing use of resources	Bilateral conflict occurred prior to action taking and was about strategic choices/planning	N/A (very little unilateral conflict)
2	Initiation of conflict	Conflict initiated by the words ‘no’, ‘wait’ and through physical interjections; these were followed by justifications in bilateral conflict only	N/A	Conflict initiated calmly as part of a deliberative conversation
3	Different uses of tools during conflict	Eraser, impact and info tools used to justify or check action results as a part of convincing partner	N/A	Eraser, impact and info tools used to justify or check action results as part of joint problem solving

conflict mainly followed the pattern of *strategic* conflict *prior to action* described above, with use of feedback from the impact and information tools as part of problem solving. These learners rarely engaged in conflict over which kind of specific land use to use.

Conflict Theme 2: Initiation of Conflict

In the no-roles condition, both kinds of conflict were often initiated through the verbal interjections ‘no!’ and ‘wait!’ and physical jockeying of tools; these objections were followed by justifications in bilaterally resolved conflict only. In the roles condition, the limited bi-lateral conflict observed was initiated calmly as part of a deliberative conversation. Use of the interjection ‘No!’ was a very common element of how **No-Roles** learners raised an objection about what their partner was doing, particularly conflict that was unilaterally resolved. Objections commonly followed the placement of the impact stamp showing either pollution or that population needs were not met; the conflict arose from learners choosing different proximal goals for their next steps (e.g. ‘We don’t need any more houses’ N6 L1@9:54). Use of the word ‘no’ seemed to be employed as a reflection of surprise or upset on the part of the other learner, an attempt to get their partner’s attention and pause the undesired action, in combination with what the other learner had said/done immediately prior, it served to communicate the content of the objection (e.g. ‘One more mountain reserve’ ‘No’.’ N8 L2@14:03, L1@14:09). In addition to such verbalizations, learners in **No-roles** pairs also used physical means to interject, often grabbing a currently unused tool to enact an alternative action or grabbing a stamp from the other’s hand or using the eraser tool to erase the result of the recent action of the other learner while saying, ‘no’ or ‘wait’. The key difference in conflicts which were resolved bilaterally was that the ‘no’ was followed by an explanation of the objection (e.g. L1 says, ‘Should we erase the coal mine?’ L2 says, ‘No [pauses] let’s see what it does . . . I know coal is good’ and places coal mine stamp into information tool, pausing interaction. L1 tries to grab the stamp. After reading the information card, they see it produces energy for a large population and they jointly decide where to place the coal mine, both grabbing the single stamp N6@8:29).

The use of ‘no!’ ‘wait!’ and physical interjections were not a theme for conflict initiation in Roles pairs. This aligns with the finding that the limited conflict they did engage in (almost all of which was resolved bilaterally) occurred as part of strategic planning (see Conflict Theme 1). For Roles pairs conflict initiation was not shaped by the urgency of needing to stop a partner’s undesirable action in-the-moment. Instead, disagreements were initiated more calmly as part of a deliberative conversation (e.g. ‘But we already have and it pollutes more . . . pollution those are bad, see?’ R1 L1@21:28). Even in the few cases where words like ‘no’ or ‘wait’ were used, context was used to soften their effect in comparison to the strong objections seen in the no-roles condition (e.g. ‘Wait a minute . . . . [places impact tool back on screen]’ R4 L2@18:33).

Conflict Theme 3: Different Uses of Tools During Conflict

In both conditions, the eraser, impact and information tools were used to justify or check the results of actions during conflict. In no-roles pairs these tools were used to convince; in roles pairs they were used to problem solve. Learners in both **Roles** and **No-Roles** pairs used the erase, impact and information tools during both bilaterally and unilaterally resolved conflict to justify or check how a stamp or series of stamps would impact the world. Sometimes this occurred when one learner took a position by making a statement and placed a stamp to justify it (e.g. ‘No don’t do anything that will add pollution’ [places impact tool] L2 in N2@9:43). Sometimes one learner used a tool to check the result of an action during the conflict (e.g. L1 stamps then says, ‘Let us see.’ and places the impact tool N3@6:53).

During bilaterally resolved conflict, learners in ***No-Roles*** pairs, mainly used tool(s) to back up their position or convince the other. This often involved a lot of grabbing of tools and stamps (e.g. a pair is trying to balance pollution and energy. L2 places the impact tool. L1 says, 'Should erase the coal mine?' L2 says, 'No . . . ' and removes the impact tool. 'Let's see what it [coal plant] does . . . I know coal is good' and L2 places coal plant stamp in the information tool ring and says, ' . . . produces energy.' L1 grabs the stamp from C2's hand and stamps a coal plant and says 'Oh that's what it does' and then uses the eraser tool to erase it. Eventually, both holding the stamp, they place another coal plant. N8@8:29). During unilaterally resolved conflict, learners in ***No-Roles*** pairs also used tools to justify or check the world state or information; however, the control of the tool(s) tended to remain with one learner. Often the type of language the learners used suggested that one learner was seeking to convince the other of their position (e.g. 'What?! Why are you erasing it?' and places impact tool L1 in N6@18:45 and then later 'No we should get rid of one of these because . . . .' and places impact tool L2 in N6@18:45).

In contrast, learners in the ***Roles*** pairs used the impact, information and eraser tools to problem solve and bilaterally resolve conflict in a more cohesive manner (e.g. two learners are trying to balance pollution and energy. L2 says, 'Do you want to try a bit more coal stuff?' L1 objects, 'But we already have it and it pollutes.' L2 says, 'Yeah but . . . ' and places impact tool on map. L1 touches pollution ring while L2 continues to hold the impact tool. L1 points to coal plants on map, and says 'Pollution. Those are bad see?' L1 agrees, 'Yeah . . . let's try and mountain reserve.' R1@21:44). Control of interaction moved back and forth between the learners fluidly as they worked together to solve the problem. While on the surface this instance may appear similar to the ***No-Roles*** interactions, the learners in ***Roles*** share the impact tool and the language is less adversarial.

8. DISCUSSION

8.1. Summary of outcome and process measures of collaborative learning (RQ1–4)

All of the pairs met the learning goals as assessed by teacher evaluations of their presentations and their own self-ratings. Teacher evaluations of quantiative learning outcome measures determined that all pairs understood the complexity involved in making land-use decisions (RQ3.O1 and RQ4.O1) and they valued achieving balance between human and natural needs (RQ3.O2 and RQ4.O2). In achieving these outcomes, all pairs worked together for the duration of the sessions to create a world they would like to live in (RQ1.P1). These consistently high positive findings may be due to Youtopia's design, but may also be attributable to prior knowledge of the learners, teacher selection of pairs who would work well together, and the effects of a generally strong collaborative school environment (Hakkarainen *et al.*, 2002).

Results of quantiative process measures showed that learners actively negotiated about trade-offs and goals, focusing on both strategic and specific decisions about the type of shared world they wanted to create. They spent 5% of their session time engaged in explanations (RQ1.P2). While both conditions engaged in similar numbers and durations of two-way explanations, roles pairs engaged in a greater number of one-way explanations (RQ2.P2). In future work it may be necessary to relax coding requirements to include a larger swath of relevant talk; however, this also highlights an important point about CSCL analyses—that the 'golden moments' in collaborative learning we aspire to (and see highlighted in the research) are often fewer and farther between than we would like to think. Learners also engaged in resolving conflicting views, both bilaterally with their partner and at times, unilaterally (missing the opportunity to negotiate) (RQ1.P3). Roles pairs had less conflict overall, but when it occurred it was almost always (with just a single exception) resolved bilaterally, and this resolution process lasted three times as long as for no-roles pairs (RQ2.P3).

Our qualitative analysis enabled us to examine how and why these quantiative differences occurred. Our analysis of one-way explanations (themes summarized in Table 7) revealed that one-way explanations for all learners were commonly retrospective in nature, stimulated by the world-state and employed collectivist ('we') language. In no-roles pairs, explanations generally presented a positive confirmation of the world state and often involved a balanced view of human and environmental concerns. In roles pairs, explanations additionally occurred in direct response to partner activity with an action orientation toward changing the situation; these explanations could be oppositional or questioning of what a partner had done with an orientation toward changing the world state. Roles pairs often stayed with their assigned perspective up until or through the end of the session; however were more likely to give explanations that included the perspective of the world's inhabitants.

Qualitative analysis of conflict events (themes summarized in Table 8) also showed that conflict in no-roles pairs was often initiated through interjections ('no' 'wait') and tool jockeying; in bilaterally resolved conflict, these were commonly accompanied by a justification of the complaint. Bilaterally resolved conflict also tended to occur prior to (rather than during) system action, related to strategic planning, and included check-ins and questions. In no-roles pairs, the eraser, impact and information tools were used to convince the other learner, often at a tactical level. In roles pairs, the same tools were more commonly used at a strategic level as part of a joint problem-solving effort.

8.2. The positive interdependence design strategy (RQ5 and 6)

The tightly coupled input design (contingent tool design) of Youtopia was in alignment with recommendations for a constrained input system that can encourage sharing and coordination (D'Angelo *et al.*, 2015; Hornecker *et al.*, 2007). This is in contrast to suggestions to enable simultaneous inputs with no constraints or only loose input coupling (allowing for interference) or providing limited inputs to enforce collaboration (Falcão and Price, 2011; Jamil *et al.*, 2017; Tissenbaum *et al.*, 2017). With our design, learners needed to use the tangible land stamps in specific two- to three-step sequences. However, these sequences could be enacted by learners in different ways, which could be facilated through spatial placement or instructions (e.g. with each learner using tools placed near them, with tools split across learners, or a single learner using tools), enabling flexible and dynamic possibilities for interaction, which was highlighted as important in (Jamil *et al.*, 2017; Rick *et al.*, 2011). The specific enactment of two learners working together interdependently was determined by learners but was encouraged by using social and physical design elements as demonstrated in the roles condition. In this approach, social conventions around roles and object ownership were leveraged so that when learners were assigned a role with their own set of associated (physically marked) land-use tools, they predominantly complied with these social conventions and worked together to co-enact input sequences. Our results revealed differences in number, duration and themes between roles and no-roles pairs, for one-way explanation-giving (see Tables 3 and 7) and conflict resolution (see Tables 4 and 8), suggesting that this form of co-enactment (as instantiated in roles) supported more rich opportunities to negotiate common ground than using coupled inputs alone (no-roles). While several other tabletop studies have used roles to structure collaboration (e.g. Tang *et al.*, 2006; Woodward *et al.*, 2018), no designs that we are aware of have used the combination of tightly coupled inputs with physically marked input tools, which are then assigned to roles to support positive interdependence between learners.

Design for Positive Interdependence and Explanation-Giving

When we examine quantitative findings, we see that both conditions engaged in similar numbers and duration of two-way explanations, however roles pairs also engaged in more one-way explanations (Table 3). Our *qualitative* analysis of one-way explanations revealed differences in negotiation between conditions. Roles pairs engaged in similar behaviors as no-roles as well as additional productive behaviors (e.g. Table 7, topics 1–4, roles). Taken together, the higher number of one-way explanations combined with additional productive forms of one-way explanations suggests a benefit for the positive interdependence condition of the roles condition. Getting learners to give explanations can have benefits, even if the explanation is not reciprocated, as learners either externalize their thinking or are made aware of the thinking of others (Clark and Sampson, 2008; Price *et al.*, 2003; Wise and Hsiao, 2019). Specifically, our qualitative findings indicated that for roles pairs, a substantial portion of these one-way explanations were given in response to an action (or comment) made by their partner (see Table 7, topic 1) and included opposing something they had done or asking questions of them to seek confirmation (Table 7, topic 4), and using 'you' language to request (or direct) their partner to take a particular action (Table 7, topic 3). One explanation is that these productive behaviors stem from the distributed ownership of tightly coupled and physically marked tangible input tools, which were assigned to roles. In the roles group one-way explanations may have been stimulated by the fact that actions taken by one learner always had implications for the other. Similarly, questions or requests for action were necessitated by the fact that providing for human needs (food, shelter, energy) required using at least one stamp assigned to each partner. Notably, while use of assigned tools was not enforced, no violations of the assignment occurred, in contrast to findings by Antle *et al.* (2011) and Woodward *et al.* (2018) where learners assigned roles and screen territories (rather than physical input objects) did not comply with their roles. Drawing on Rick *et al.*'s (2009) finding that learners took more responsibility for the parts of the tabletop surface closer to their relative position, this may be in part due to the initial presentation of role stamps on opposite sides of the table. These norms of social ownership of tangible objects have been seen in other studies (Speelpenning *et al.*, 2011) and in our design they even extended to use of the shared eraser tool to remove elements associated with each role.

The extent to which our design strategies impact the different character (and additional quantity) of roles pairs explanation-giving has implications for the learners being open to, or actually changing, their ideas and is an important area for future research. Learners' efforts to seek confirmation or agreement from their partner suggests some attempt toward establishing common ground in terms of goals (Beers *et al.*, 2007; Dillenbourg, 1999) and understanding of the task (Coleman, 1998). Through this form of negotiation learners may move toward the desired end of thinking beyond their own personal views (Teasley, 1997; Vogel *et al.*, 2016; Wen *et al.*, 2017). This inference is also supported by the finding that learners' comments considered the welfare of the world inhabitants in roles pairs (See Table 7, topic 6). Oppositional explanations (Table 7, topic 4) may also be valuable for stimulating learning as they potentially push learners to reconsider their ideas about what their ideal world looks like in ways that the positive evaluations (which dominated in the no-roles condition) do not (Weinberger and Fischer, 2006). Further research is needed to explore these propositions.

Conversely, many learners in the roles pairs stayed on 'their' side of the issues (human needs or the environment) for the majority of the session, rather than progressing to a more balanced position in which they individually acknowledged the trade-offs involved. They also reported lower ratings of the benefits of working together and of the value of balancing natural and human needs. This is likely because in no-roles pairs each learner could take on either stance and this enabled them to better understand both positions rather than just a single assigned one. This distinction between a shared task, and shared goals is noted in (Tissenbaum *et al.*, 2017) and may apply here. This suggests that a hybrid design strategy promoting both opposition and togetherness may be desirable. One approach to this could be via task phases where roles/controls are scripted at the beginning but either switched or deliberately released partway through. Another approach could create both individual and shared responsibility for different simulation elements (e.g. one learner is in charge of housing, one is in charge of energy and they are both in charge of food and the environment). This would have the potential benefit of creating an obligation to the game-world, causing some opposition between the learners, but also triggering them to consider where the best balance lies (since there is a trade-off between the environment and each human need). More research is needed to explore these design variations.

In summary, there are several advantages of our design approach relative to enabling *explanation-giving* during collaborative learning. First, in contrast to other work, in which prompts were necessary as scaffolding to support explanation-giving (Yannier *et al.*, 2013), with Youtopia explanations emerged as a result of interactional processes enabled by our tightly coupled (contigent) input system design and strengthened by physical-social assignment of input tools. Second, another advantage of tightly coupled tool design is that learners can physically interact in flexible ways (Jamil *et al.*, 2017) and socially interact in different ways (Rick *et al.*, 2011; Woodward *et al.*, 2018) and these different forms of interaction can be explicitly supported by the way that tools are presented to learners. And lastly, these role-based constraints can easily be modifed during learning tasks, making our design flexible in how it can be adapted to or respond to group dynamics and the needs of individual learners. For example, the assignment of roles could be used for learning scenarios in which learners may initially have divergent rather than shared goals (Tissenbaum *et al.*, 2017), however, roles can be released to enable learners to work toward shared goals and perspectives during the task.

We suggest that these advantages may generalize to other mixed reality environments with similar affordances. For example, a multi-user (distributed) augmented reality environment could be designed using contigent inputs. These could be digitally augmented physical input tools or digital-only tools which are visible to all learners through their augmented reality headsets or tablets, but only active for assigned roles. These kinds of instantiations of our approach may have similar positive impacts on explanation-giving such as those found in our study. We have begun this exploratory research by developing a tablet-based augmented reality version of Youtopia with a virtual contigent digital tool design and assignable roles (Sarker, 2019). Further research is needed to explore how to apply our design strategy to other platforms that enable distributed group controls and if doing so results in beneficial interactional processes that are similar to ours.

Design for Positive Interdependence and Conflict Resolution

Examining conflict events, we found that the no-roles pairs had more unilaterally resolved conflict (as predicted) but also more bilaterally resolved conflict. Roles pairs had a longer session time by three minutes, and some of this time may be accounted for by significantly longer (although fewer) bilaterally resolved conflicts. Such bilaterally resolved conflict in the roles condition often included joint tool-based problem solving at the strategic (rather than tactical) level, which is a form of productive argumentation (Mercer, 1996; van Boxtel *et al.*, 2000; Vogel *et al.*, 2017). Bilateral conflict in roles pairs also occurred largely prior to action. It may be that the assignment of roles and tools supported is a more intentional stance toward world-building, possibly because learners were pausing to reflect from the perspective of their assigned role. The assignment of roles and tools appears to have almost eliminated adversarial interactions, which detract from opportunities for negotiating common ground: issues that have been explored or observed in other studies (e.g. Falcão and Price, 2011; Jamil *et al.*, 2017; Woodward *et al.*, 2018). It is possible that the observed productive engagement with a partner's intended actions in the roles condition (only) may have related to the shared responsibility created by our positive interdependence design strategy. Instead the strategic problem-solving nature of these (limited) bilaterally resolved conflict events suggests a form of argumentation that may have led to understanding of alternative perspectives, and updating personal and shared understandings (Nussbaum and Sinatra, 2003; Weinberger *et al.*, 2013, p. 333). It also is possible that these bilateral conflict events may have led to more complex and meaningful knowledge structures, although there is no direct evidence of these as both groups met learning outcomes (Schwarz and Asterhan, 2010). Again, more research is needed, including a focus on the impact on different instantiations and variations of design strategies on interaction, and a more nuanced assessment of outcomes.

In contrast, in no-roles pairs, although there was more of both types of conflict, it had characteristics that may have been less productive in establishing common ground. Overall no-roles conflict was more adversarial in nature and often included physical jockeying over tools or other blocking strategies, such as those seen in (Falcão and Price, 2011; Jamil *et al.*, 2017; Woodward *et al.*, 2018). In addition, when interjections ('no', 'wait') were used to initiate conflict without a justification of the reason, the conflict was usually resolved unilaterally, missing the opportunity for productive negotiation (Mercer, 1996). No-roles conflict also commonly focused on the use of a specific resource (rather than a strategic choice), a finding mirroring that of (Olson *et al.*, 2010). Finally, the impact, information, and eraser tools were used during no-roles conflict to justify each partner's position rather than to jointly problem solve. A plausible explanation is that shared tools are valuable for exploring the impacts of different strategies and perspectives within roles, suggesting a design strategy of including both assigned and shared tools, a similar strategy to that suggested in (Antle, 2014).

In summary, the advantage of our technical-physical-social design approach relative to *conflict* during collaborative learning is the reduction of negative behaviors (e.g. physical interference) that detract from establishing common ground through productive conflict resolution.

8.3. Collaborative interactions and the reflective pauses design strategy

Across all pairs, the impact, information and eraser tools were commonly used in conjunction with both explanation-giving and conflict resolution. Specifically one-way explanations commonly occurred in conjunction with use of the impact tool and the impact, information and eraser tools were used during conflict resolution to justify a position, check how a stamp would impact the world or jointly problem solve. There are several aspects of the tools' design that may have contributed to this. First, as intended, the impact and information tools stopped interaction, creating a space to 'step-out' of the action and take time to explain one's thinking (Ackermann, 1996; Antle, 2014). Price *et al.* (2010) discuss similar opportunities for complementary reflection and action during a study of learners exploring optics with a tabletop tangible activity.

Second, the on-demand mode of communicating this information, triggered by one or both learners, created opportunities for both shared focus and discussion, in alignment with findings by Antle (2014). Prior work on collaborative learning has stressed the importance of referential anchors (Clark and Brennan, 1991) and other mechanisms that draw learners' attention to each other (Antle, 2014; Fernaeus and Tholander, 2006; Price and Pontual Falcão, 2011). In Youtopia, the world maps serve this purpose in a general way. However, the graspable physical design of the tools, which stop interaction and trigger their own displays, may create a hybrid *physical, visual* and *interactional referential anchor* that draws both learners' attention and actions to the same digital object, providing shared interactional opportunities (e.g. touching shelter, food, housing rings on impact overlay). The creation of hybrid physical-visual tools that scaffold reflection through pauses in the main flow of interaction may work well in augmented reality spaces. For example, one learner could scan a physical tool to trigger graphical overlays in all learners' augmented displays (head-mounted or tablet-based). Further research is needed to explore these hybrid design opportunities to provide space and scaffolds for reflection during collaboration.

Third, it is notable that both the impact display and information cards provided feedback in ways that were intentionally value-neutral, which Antle *et al.* (2014b) suggests may encourage learners to state their own reasons and values. For example, the pig's speech bubble asked 'Is this a world you want to live in?', so the circular scales of the impact display for pollution, shelter, food, and energy could be viewed from either a 'half-full' or 'half-empty' perspective. The information tool brought up a scalable and rotatable card containing world facts in the form of information about land-use causes, effects and productivity. Again, information was presented in value-neutral ways using phrases such as this resource can 'meet the needs for a large/small population'.

Lastly, the tools can be conceptualized as providing mechanisms for 'back-talk' during a design task; that is, providing valuable world-based information in the context of the world-making task at hand (Zhang *et al.*, 2018). The presence of an eraser tool that allowed learners to endlessly undo and redo actions—creating bidirectional pathways through the task—may play an enabling role in supporting cycles of experimentation, evaluation and change (Antle, 2014; Fleck *et al.*, 2009; Tissenbaum *et al.*, 2017). Providing learners with avenues during their hands-on exploration of the task for 'back-talk' of a form that prompts reflection has also been suggested as an effective design strategy (Slovák *et al.*, 2017). Taken together these system features appeared to be effective here in eliciting learners to share their evaluations of the world, and the reasons for them, with each other.

It is interesting that while no-roles pairs tended to refer to the impact tool to reflect on what was (already) good in the world, roles pairs also used it to point out what could be better. The root cause of this difference is not clear. In (Wise *et al.*, 2012) the authors suggest that this type of pattern may be related to a greater feeling of responsibility for the task (world) imparted with the assignment of roles. There is also evidence for this in the connected language used by roles pairs to talk about the experiences of people in the world (rather than the detached language used by no-roles pairs). Whether a heightened sense of responsibility and forward-oriented talk is advantageous for learning remains to be examined; we suspect there may be benefits for cognitive engagement from learners feeling accountable for their activity and actively comparing the world-state with the one they would like to build, rather than simply admiring the current one (Chi and Menekse, 2015). There is some evidence in the current study to support this view in that the more desirable bilaterally resolved conflict frequently took place prior to action and had a strategic character (in contrast to conflict during action, which commonly related to competing use of resources and was resolved unilaterally).

It is likely that the feedback and undo capabilities of the impact, information and eraser tools played a role in supporting a forward-looking view in explanation-giving. This also highlights that 'reflective' activity can contain both retrospective and prospective elements, with the latter playing an important role in negotiation that drives learning. In future work, the nature and value of prospective reflection can be tested empirically with designs that intentionally lead learners to reflectively take one perspective or the other (for example the pig could ask different questions: 'What is good about this world?' versus 'What can make this world better?') and evaluate the resultant talk and learning. The optimal situation may involve fluid flow between the two perspectives; thus could be encouraged in various ways (e.g. the system rotates between different prompts or prompts whichever perspective is less represented). Another design strategy would be to create an additional ‘opinion’ tool. The tool could support the reflective pauses strategy in order to maintain a working partnership while also enabling learners to express their individual views (like a newspaper commentary). For example, the tool could also stop interaction, display particular aspects of world state and offer opportunities to express different opinions on how (if at all) they should be addressed. Again, these strategies are well suited to support group members to engage productively with each other in a variety of hybrid physical–digital environments.

Taken together, our current and proposed strategies for designing supports for roles and assigned and shared tools warrant further study, as they may positively impact the learning processes related to negotiation of common ground in a range of trade off-based learning domains on physical–digital, multi-user platforms including tangibles, digital tabletops, hand-held devices, augmented reality and other emergent technologies.

9. CONCLUSIONS, LIMITATIONS AND FUTURE WORK

This paper presents the results of an in-school experimental study on the effects of positive interdependence and reflective pause design strategies on a collaborative activity in Youtopia, a tabletop sustainability simulation. In particular, we examined the impact of instantiating (i) positive interdependence through the assignment of roles (natural resource, human development) with contingent land-use tools and (ii) reflective pauses through the inclusion of impact, information, eraser tools and error tabs. We conducted a mixed methods analysis to understand how these design strategies stimulated interactional processes, including explanation-giving and conflict-resolution, which form part of the negotiation of common ground.

All learners met the learning goals for topics related to the environment and sustainability. Our evidence indicated that the overall design of the tangible tabletop sustainability simulation, which was based largely on prior design guidance and recommendations, supported this positive outcome. More importantly, we have shed light on understanding how learners interact with tools desgined for a complex, spatial, and value-laden sustainability simulation task. In doing so, we provide further guidance to better understand how and why design features’ support for positive independence and reflective pauses may lead to interactional processes that support learners to negotiate common ground in a collaborative learning task.

The strategy of layering social practices related to the assignment of roles and associated (marked) input tools on top of a technical strategy of implementing tightly coupled (contingent) inputs to enable positive interdependence was associated with more one-way explanations involving externalization of thinking, world inhabitant perspective taking, and prospective, strategic level joint problem solving of conflict, all of which helped to create common ground for the shared task. Conversely, learners in the no-roles condition showed more evidence of exploring both sides of nature-development trade-offs, which is also important in value-laden topics such as environmental and sustainability education. The strategy of using different types of tangible tools to enable reflective pauses was associated with learners taking actions to jointly explore the task, stopping interaction to ‘step-out’ to reflect and engage in dialogue about the task and each other’s perspectives as they negotiated toward common ground. The physical–digital nature of the tools acted as visual and interactional referential anchors that drew learners’ attention to each other and elicited explanations. When combined with the assignment of roles, these tools enabled strategic and prospective problem solving and productive resolution of conflict through collegial negotiation.

There were several limitations to this study relating to the relatively small sample size, learners with atypically high prior knowledge and experience collaborating, and the high bar of coding criteria for explanation events. Future work should expand the number and diversity of learners studied with a more liberal coding protocol. Other areas for future research include developing and testing social-technical design strategies for stimulating perspective taking from multiple angles (partner, world inhabitants, human development, environment preservation) and facilitating retrospective and prospective problem solving, as well as supporting expression of individual and joint values, opinions and agency. Future work should also explore how to adapt these design strategies to other platforms that enable distributed control in hybrid physical–digital environments (e.g. mobile and head-up display-based augmented reality, tangibles, networked hand-held devices) and investigate the kinds of interactional processes that result, with an eye on the kinds of beneficial processes shown to support collaborative learning.

In summary, this study addressed two central challenges in designing interactive tangible tabletop applications for collaborative learning: (i) finding ways to distribute activity across a group and (ii) getting group members to coordinate this activity by engaging with each other constructively. Our results and suggestions for design to support collaborative learning may also generalize to interaction design for other mixed reality platforms. In particular, our findings revealed important considerations for achieving these goals through the instantiation of the design strategies of positive interdependence and reflective pauses, showing both quantitative and qualitative differences in the interactional processes that result. These findings contribute to a growing body of knowledge about how and when particular design strategies for collaborative learning applications that involve technology-mediated objects for control create conditions that enable productive collaborative learning processes that can contribute to desired learning outcomes.

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