Exploring How a Co-dependent Tangible Tool Design Supports Collaboration in a Tabletop Activity

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ABSTRACT
Many studies suggest that tangibles and digital tabletops have potential to support collaborative interaction. However, previous findings show that users often work in parallel with such systems. One design strategy that may support collaboration rather than parallel use involves creating co-dependent access points in which each user must act in order to create a system response. To better understand how co-dependent access points support collaboration, we designed a comparative study with twelve adults using the same application with co-dependent and independent access points. We collected and analyzed categories of both verbal and behavioural data in the two conditions. Our results show support for the co-dependent strategy and suggest three design strategies for supporting collaboration on tangible tabletops.

Author Keywords
Tangible user interfaces; digital tabletop; interactive surfaces; co-dependent access points; collaboration; adults.

ACM Classification Keywords
H.5.3 [Information interfaces and presentation]: Group and Organization; H5.2. Information interfaces and presentation: User interfaces.

INTRODUCTION
Much research has been conducted to explore how to better support collaboration on digital tabletops. The large size of digital tabletops enables users to view and manipulate tasks together, which makes it easy for them to perform collaborative activities [23]. More recently, tangible user interfaces have been used in conjunction with digital tabletops to facilitate collaborative interaction [25]. Tangible tabletops allow people to leverage existing collaborative strategies with physical objects, and the physicality of objects may support awareness in collaborative activity [24, 25].

Results from different studies of the same design strategies reveal disparate results [16]. For example, multiple physical access points offered by tangible tabletops have been shown to promote synchronous collaboration [25]. However, other results suggest that this approach can also lead to parallel work between users [16]. Based on these mixed results, more research is needed to determine how to support true collaborative activity rather than independent parallel activity. Antle *et al.* [1] suggest that one approach that may support collaboration rather than parallel use is to create co-dependent access points in which each user must act in order to create a system response. There are no studies that specifically explore the following research questions: *(RQ1) Do co-dependent access points more effectively support collaboration on tabletops than independent access points for adults? (RQ2) What kinds of collaborative behaviours and interactional patterns do co-dependent and independent access points for tangible tabletops each support?* Addressing these questions adds value through better understanding potential design problems in order to help designers formulate effective design strategies for collaborative, tangible tabletop interfaces.

In order to address our questions, we conducted a comparative study with 12 adults ----between 20 and 28 years of age----who used a hybrid tangible, multi-touch tabletop application that supported collaborative land use planning activity. The application's name is removed for blind review in this paper, and it is called "the system." In this paper, we present the results of our analysis comparing levels and types of verbal negotiation and physical collaboration in two conditions: co-dependent and independent access points. We discuss the implications of our results and propose three design considerations for the design of collaborative hybrid tangible digital tabletop applications.

RELATED WORK
Characterizing Collaboration
There is no single definition of collaboration or collaborative activity. According to Goos *et al.* [9], collaboration is a reciprocal, coordinated interaction in which ideas and perspectives are explored and exchanged. Dillenbourg [6] views collaboration as a situation in which interaction and negotiation must happen between participants to successfully complete a task. This definition

stands in contrast to cooperation, in which people may still work together to accomplish a task but negotiation and interaction are not necessary. Negotiation plays an essential role in collaboration [26]. Collaborative activity needs the negotiation not only of task-related content, but also of task structure in terms of roles, activities, and sub-task allocations [5]. Dillenbourg's definition also suggests the importance of equitable participation – both verbal and physical for hands-on tasks. Equitable participation helps team members to better understand each other, adjust plans, and achieve the shared goals.

Designing for Tabletop Collaboration

Multi-touch and tangible digital tabletops have been suggested as one way of encouraging productive synchronous collaboration. However, the empirical findings of previous studies are contradictory [20, 24,16,21].

Several studies suggest that multi-touch tabletops enable more synchronous collaboration than traditional user interfaces [20, 22]. Traditional computer technologies, such as a single mouse with PC, do not allow synchronous activity for multiple users [20]. The single mouse situation forces users to share a single input and often results in frustration and reduced engagement [13, 22]. In contrast, multi-touch tabletops enable multiple users to simultaneously engage in the same activity, which may simulate synchronous collaboration and avoid conflict over input controls (i.e., 'cursor wars'). For example, the multi-touch system *DiamondTouch* [7] allows for synchronous collaboration among multiple users as well as multiple simultaneous touches from a single user. The *CollabDraw* [17] uses cooperative gesture interaction techniques to support collaborative art and photo manipulation.

Benford *et al.* [3] present different approaches to interface designs that *enable, encourage* or *enforce* collaboration. *Enabling* collaboration refers to providing multiple access points that allow users to participate simultaneously. E*ncouraging* collaboration refers to offering an incentive or functionality that encourages collaborative work. *Enforcing* collaboration refers to functionality that enforces specific collaborative actions, such as turn-taking. Encouraging collaboration is more proactive than only enabling collaboration, but not as rigid as enforcement [19].

Combining tangible objects with multi-touch tabletop interaction may improve users' awareness of each other's actions and tool use [11, 24]. For example, Speelpenning *et al.* [24] conducted an exploratory study to compare the differences between tangible and multi-touch tool use and the impact of tool use on collaboration in a digital tabletop game. Observational findings suggested that the physicality of the tangible tools facilitated individual ownership and announcement of tool use, which in turn supported awareness of each other's actions, and therefore more effective support for collaboration.

Tangible objects provide multiple access points to a tabletop application, which may lead to parallel rather than collaborative activity [16, 21]. Several design strategies have been explored to avoid parallel use. For example, in a tabletop computing game called *SIDES* [18], turn-taking was used to regulate and ensure each individual's equitable participation in collaboration. However, this approach forces people to work together rather than encouraging them to collaborate, which results in less flexible collaboration.

An alternative approach suggested by Antle *et al.* [1] is to create co-dependent access points in which each user must take action in order to create a system response. Access points represent the potential of multiple input elements that enable users to interact and participate in a collaborative activity [10, 12]. Compared to the *enabling* or *enforcing* design strategies, the co-dependent access points approach has the potential to *encourage* equitable collaboration without restricting it. Research is needed in order to better understand *whether* co-dependent access points are more effective for enabling collaboration than independent access points and *how* these two access points strategies support collaboration in a tabletop activity for adults.

Analyzing Tabletop Collaboration

Analysis of collaboration focuses on verbal and physical behaviors that people use to mediate collaborative activity [20]. The amount and type of explicit communication can indicate the degree of collaboration [8]. For example, verbal negotiation, such as talk or dialogue, plays an essential role in sharing mutual understanding among participants in face-to-face collaboration. Studies [14, 10] suggest that various types of talk patterns are important in collaborative activities around tabletops. Jamil *et al.* [14] discuss how different tabletop designs lead to different talk patterns during collaborative activity. Similarly, Harris *et al.* present results from a comparative study of multiple-touch and single-touch collaborative interaction on a tabletop activity, wherein a coding system of talk types was developed to measure the level of collaboration [10].

Physical interaction is also important in collaboration analysis. In a study presented by Hornecker *et al.* [11], they demonstrated that large surfaces provided users with opportunities to physically organize objects in space in order to support collaborative activity. The size of the surface also allowed each member to be visually aware of the activities of other members.

SYSTEM – DESCRIPTION OF THE PROTOTYPE

Our system (*name removed for blind review*) is a collaborative hybrid tangible multi-touch tabletop sustainable land use planning activity (Figure 1). It was designed, in part, to evaluate how co-dependent and independent tool designs influence collaboration between users.

The System

The system consists of a set of tangible computing stamps and a multi-touch tabletop display. The main form of interaction with the map is through placing or stamping physical stamps. There are two main kinds of stamps. A secondary form of interaction is the use of multi-touch interaction. A complete description of the system can be found in [*removed for blind review]*.

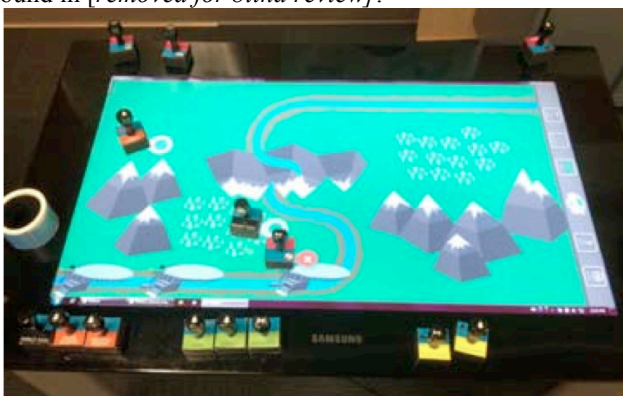

Figure 1. [Name removed]: a collaborative hybrid tangible multi-touch tabletop sustainable land use planning activity.

Land use Stamps

Land use stamps can be used to either designate natural resources as usable for later development or as "builder" stamps to designate spaces for food, shelter or energy developments. For example, in order to create a single house unit (shelter), a user must stamp the "lumber tool" on the forest to designate the lumber from the forest as usable. Then s/he must use the "single house" stamp to place a housing unit somewhere in the available grasslands (Figure 2).

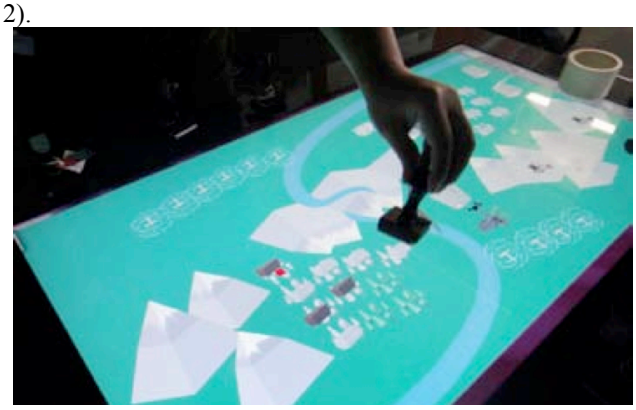

Figure 2. Stamping trees into lumber units.

Tool Stamps

A set of three additional stamps provide tool functionality, including erase, impact or world state, and more information about other stamps. The eraser stamp undoes previous stamp actions. When placed anywhere on the map, the impact stamp displays an information overlay about the current state of the world in terms of the proportion of the populations' needs being met for food, shelter and energy, as well as displaying the world's pollution level. Placing any stamp in the information ring displays a detailed information overlay about that stamp. Users can rotate or scale the information overlay to share it using multi-touch. Both impact and information tools provide a freezing screen feature whereby all other functions are inactive when these stamps are in use (Figure 3).

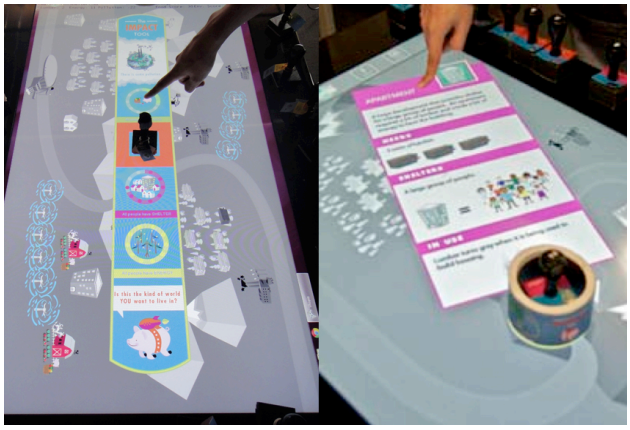

Figure 3. Impact tool and information tool –freeze the display.

Scenario of Use: Co-dependent and Independent Modes

The system can be used in two modes based on the instructions given to the users. In the *co-dependent mode*, the natural resource stamps are given to one person assigned the role of natural resource planner, and the development stamps to another assigned the role of developer. In the *independent mode*, users do not have any roles and they can use any stamp.

The application begins with an undeveloped landscape that contains areas of natural resources (e.g., trees, river, coal reserves in mountains) and other "open" areas (e.g., grasslands). Participants use the stamps to designate what use will be made of each specific space on the interactive map. They can designate natural resources for preservation or use, and build food, shelter or energy sources to try and support either a small or large population's needs. The balance of preserving the natural environment while meeting the population's needs is up to the participants. The system provides no explicit feedback on winning or losing in order to allow participants to explore options according to their values.

STUDY METHODOLOGY

Study Design

In order to understand how co-dependent (CD) and independent (ID) access designs affect collaboration, we designed a comparative study. In the CD condition, pairs were asked to play with a specific role and only use their own stamp tools. In the ID condition, pairs did not have roles and they could use all stamp tools. A within-subjects design was used because group dynamics and participants' personalities can influence collaboration [15]. To control for order effects, conditions were counterbalanced; half the group was assigned to the CD group first and the other half was assigned to the ID group first.

Participants

We collected data from 12 participants (4 males and 8 females) who played the activity in pairs. The participants were graduate and undergraduate students from our university. Their ages ranged from 20 to 28 years old. All participants reported that they had used a touch surface before (e.g., smart board, iPhone, iPod). Most participants reported that they had used a digital tabletop (8 out of 12) and a TUI (8 out of 12) before. However, none of them had played our system before. The groups were randomly assigned and so participants knew each other to different degrees: some were classmates or friends (8 out of 12) while others did not know each at all (4 out of 12). Pairs in four groups were a male and a female while in two groups there were two females. Participants were rewarded with a $5 for participating in our study.

Task

The task was to *"create a world that you like to live in, which includes creating enough food, shelter and energy for a small population."* Participants used a different but equivalent map in the second condition to control for learning effects. In each condition, participants had 10 minutes for this task. There was no fixed approach or "winning state" for the task. Participants could use different stamp tools to achieve the goal. For example, in order to make shelters for a small population, participants could use any combination of apartments, townhouses or single-family dwellings.

Procedure

Our land use planning application was set up on a Microsoft Surface table in a controlled lab space. A survey was given to participants to collect the demographic data, including their name, age, relationship with the other player, and previous usage/experiences with similar technologies. We demonstrated the system and gave participants a basic tutorial. Then each group had five minutes to familiarize themselves with the system. When participants felt ready to begin, they were given the task. Each group worked on the same task for each of the two conditions, changing every 10 minutes. Overall, the two tasks lasted for 20 minutes. A post-interview was given to participants once they completed the tasks in each condition.

Data Collection and Analysis

Our mixed methods approach involved collecting data including video (V.), structured observations (S.O.), system logs (S.L.), and post-interviews (P.I) in order to analyze verbal negotiation (V. & S.O.), physical actions (V. & S.L.), interactional patterns (V. & S.O.) and participants' thoughts about working with each configuration (P.I.).

We used quantitative methods to address our first research question (*RQ1*). Quantitative methods consisted of measuring the level and equity of verbal negotiation and level and equity of physical interaction in the CD and ID conditions. We used descriptive statistics (median/range, mean/standard deviation) to analyze the data.

We then adopted qualitative methods to investigate our second research question (*RQ2).* Qualitative methods included observing different types of verbal negotiation and physical actions, identifying interactional patterns, and participant's thoughts about their collaborative work in the CD and ID conditions.

Level of verbal negotiation

Level of verbal negotiation refers to the duration of task-related utterances that both participants made during the task session [10]. Each participant's task-related talk is defined as his or her own utterance. The total duration of each participant's utterances was counted (P1.D, P2.D.). Then the length of duration made by each participant was summed (D=P1.D+P2.D) to calculate the level of verbal negotiation in each session (10 minutes).

Structured observational sheets with four options (none, few, some, many) were used to collect ordinal data of the overall levels of verbal negotiation in each group in both conditions. If the participants did not talk in the entire gameplay, it represented 'none' (D was zero). If they almost constantly talked to each other (D was no less then 7.5 minutes), it meant 'many.' One researcher observed participants' verbal negotiation and selected the corresponding option. The ordinal data was then converted to a numerical range of 1 to 4, with 4 being many. The results were analyzed using descriptive statistics (median, range) to determine the differences in the level of verbal participation between the two conditions.

Equity of verbal participation

Equity of verbal participation refers to the differences in the duration of utterances between two participants during the task session [10]. The equity of utterances can reflect the degree of an individual's participation. We calculated the difference of the duration in terms of each participant's utterances. If the difference was less than approximately 2 minutes, it was considered most equitable. If the difference was more than 5 minutes, then verbal participation was unequal.

The categorical data of equitable participation between participants (unequal, some equity, most equity) was collected in each session. We then turned the categorical data into a numerical range of 1 to 3, with 3 being most equitable. The results were analyzed using descriptive statistics (median, range) to determine the differences in the equity of verbal negotiation between the two conditions.

Level of physical interaction

Level of physical interaction refers to the total number of touches and tool uses during the task session. System logs were used to collect the data including the total number of (a) stamp uses, (b) function tool use (eraser, impact and information tool), (c) touches on feedback error, and (d) touches on the impact tool. We collected interval data of participants' physical interaction and presented the mean and standard deviation (SD).

Equity of physical participation

Data sets from system logs could not indicate which user took each action. We used a video camera to record participants' actions and distinguish each participant's stamping actions and touching actions based on both video and system log datasets. By counting the number of stamping and touching actions per participant, we could compare two participants' physical participation in each condition. Mean and standard deviation were presented in the analysis.

Types of verbal negotiation

We were also interested in the content of verbal negotiation as well as the similarities and differences between the CD and ID conditions. We iteratively developed coding of types of verbal negotiation based on the literature review [10, 14] and pilot studies before the experiment. The final categories included:

1. Task focused discussion and negotiation (e.g., strategies)
2. Information exchange (e.g., instructions)
3. Conflict dialogues (e.g., disagreement)

Structured observational sheets and video data were used to analyze participants' types of verbal negotiation in order to gain insight into *how* participants negotiated and *what* the similarities and differences were between the two conditions.

Type of physical action

Type of physical interaction refers to different physical patterns that emerged during system use. We focused on physical actions between participants. The coding themes were developed prior to experiment [10]. The main patterns of physical interaction consisted of the following types:

1. Purposeful actions or gestures (e.g. pointing to a place on the map, passing tools to each other)
2. Contents sharing through tools and multi-touch (e.g., rotating or scaling contents for the other)
3. Conflict use of tools (e.g., grab tools at the same time)

We analyzed *which* type of physical actions emerged during the CD and ID condition and *how* participants specifically used these actions to collaborate in different conditions.

Interactional patterns

Interactional patterns refer to how participants worked with each other during the task. We hypothesized that co-dependent access points might support collaborative rather than parallel work. We were interested in the interactional patterns that participants developed to coordinate their work in tasks. We used observational notes, video data and post-interviews (with one open-ended question for each participant: *How do you think the different set-ups impacted your collaboration?*) to help us analyze the potential interactional patterns.

RESULTS

Our results provide insight into the similarities and differences in collaborative behaviors between the CD and ID conditions. Quantitative results provide information about levels of verbal negotiation and physical interaction while qualitative findings reveal types of verbal negotiation, physical interaction and working strategies.

Level of Verbal Negotiation

There was no difference in verbal negotiation between two conditions (Table 1). We observed that five groups actively talked with each other in both CD and ID conditions, while one group had little conversation in both conditions.

Although the average levels of the verbal negotiation in the two conditions were similar, we noticed that when participants started parallel work in the ID condition, they stopped verbal negotiation, perhaps because they did not need group awareness for independent work.

	CD Median (Range)	ID Median (Range)
Level of verbal negotiation *(median level per session)*	4(2)	4 (3)
Equity of verbal participation *(median level per session*	3(1)	2 (1)

Table 1. Verbal negotiation and equity of verbal participation (Level: 1=None, 2=Few, 3=Some, 4=Many) (Equity: 1=Unequal, 2=Some equality, 3=Most equity)

Equity of Verbal Participation

More pairs in the CD condition participated equally in verbal negotiation than in the ID condition (Table 1). Participants in both conditions usually had turn-taking talk patterns. Yet we found the duration of their verbal utterances were different.

Since participants had their own roles and tools in the CD condition, they had to discuss with the partner in order to complete the task session. As shown in the following excerpt, we found that co-dependent use of tools promoted more equitable contributions.

[P9 is the natural resource planner and P10 is the developer. Relationship: Friends]

P9: We have to do some shelters?
P10: Yes. We can do them at that area [Pointing to a certain place on the map].
P9: Okay. But as for the lumbers, we have to do (them) here [Stamping lumbers in the forest]. I will have three for, for…
P10: for a townhouse [Stamping a townhouse on the map]

In the ID condition, we often observed that one participant played a "dominant role" by proposing strategies or offering information to the other participant. Conversely, the non-dominant participant often asked the dominant person for suggestions or confirmations in the decision making process. The "no roles" configuration decreased the equitable participation from both players.

Level of Physical Interaction

The mean number of physical interactions in the CD condition was higher than in the ID condition, but we also found a much higher standard deviation in the CD condition (Table 2). We noticed that the differences originated from the stolen tools and competitive work in one CD group. The competitive work encouraged more interactions, but it actually led to independent use of tools. Because we encouraged but did not enforce tool assignment, this situation could develop.

We also found that pairs used the impact tool more often in the CD condition than in the ID condition (Table 2). It is possible that encouraging co-dependent use of tools may make pairs focus more on checking progress as part of their world building strategy.

	CD Mean (SD)	ID Mean (SD)
Level of physical interaction *(mean # events per session)*	94 (24.1)	85 (14.9)
Level of the impact tool use *(mean #uses per session)*	10 (8.2)	6 (5.2)

Table 2. Level of physical interaction and impact tool use

Equity of Physical Interaction

The equity of physical participation between pairs in the CD condition was much better than that in the ID condition (Table 3). The results were also consistent with our observational findings. In the ID condition, we found that it was common for one participant to conduct all the actions while the other only offered verbal suggestions without physical involvement. An example is presented below:

[No role. Relationship: Strangers]
P2: What do you want, houses or townhouses?
P1: Houses. We need houses, but probably not close to here [Pointing to the hydro dam] because… Why don't we move the hydro to here [erasing the hydro in the center and rebuilding it on the edge of the map].
P2: Okay.
P1: Far away (from the forest).
P2: Now where do you want to build the house?
P1: Both these areas will be fine. Here [Pointing to the forest] or here [Pointing to grasslands close to forest].

	CD Mean (SD)		ID Mean (SD)	
Equity of physical participation *(mean # events per session)*	**P1**	**P2**	**P1**	**P2**
	50 (12.4)	44 (17.0)	50 (14.7)	35 (13)

Table 3. Equity of physical participation between players

Types of Verbal Negotiation

Task focused negotiation

People in both CD and ID conditions spent a large amount of time discussing their vision and strategies. The most common themes were what kind of a world they intended to have (the overall vision) and how specifically they planned to build it (their strategies).

Although people in both conditions talked about their tasks and strategies, we found there was a slight difference in the ways they spoke about them. In the CD condition, we noticed that in 3 out of 6 groups, both players used declarative sentences to state their opinions. Participants were more deliberative about their decisions when they controlled their own tools, which gave their contributions more equal weight in the decision-making process.

[P1 is the natural resource planner and P2 is the developer. Relationship: Strangers]
P2: Then let's have some garden.
P1: So (we need) irrigations.
P2: Gardens. Garden is three or farm is three… Oh, three [Checking the feedback tab].
P1: I will give you four.
P2: We need more food. (But) we don't have enough water.
P1: Take this one off [pointing to the hydro dam].
P2: Yes, and then use (coalmine)[pointing to the coalmine].

In contrast, when people (3 out of 6) worked together in the ID condition, they tended to ask for confirmation first before conducting the next action. It was common to see a non-dominant participant ask the other for suggestions in the decision making process. Similarly, when the dominant participant attempted to make any movement, he/she also informed the other one.

[No role. P1: dominant role P2: non-dominant role]
P1: As for the energy, let's do hydro because it is clean enough. Coalmine [pointing to the stamp] is not clean. Right?
P2: Okay.
P1: We probably do here [Pointing to a certain place on the map]?
P2: Yes.
P1: Hydro can be built only on the river [Reading the feedback tab for P1].
P2: And, then, we need house. You want the house or the townhouse?
P1: Probably house. We want [to] build a house. Maybe not close to here [hydro].
P2: Yeah.

Information exchange

We observed that participants sometimes exchanged information or taught each other about how to use the system in both CD and ID conditions. Compared to the task-focused discussion, there was a low level of discussion related to information exchange. We did not observe any obvious difference between two conditions. Instead, order affected the levels of information exchange. Most of the information exchange occurred during the first session of the experiment.

People used several ways to exchange information. The most common way was directly asking. If one participant had doubts or concerns, they simply proposed questions to the other player.

We found that people used "reading aloud" as a natural approach to exchanging information and sharing peripheral awareness. When participants intended to make any actions, they attempted to speak it out. Similarly, if they were

reading the texts on feedback errors, they also read it aloud for their partner (Figure 4).

Conflict

We found that two groups had some conflict in the CD condition while none occurred in the ID condition. The conflict stemmed from their different thoughts about how to make appropriate decisions based on their own roles. In part, this may be because participants were more dedicated to their own responsibility in the CD condition, which encouraged more negotiation. Sometimes the negotiations involved conflict, which was not always resolved.

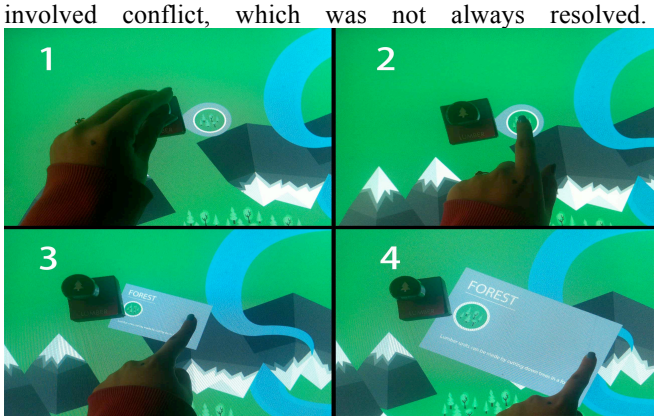

Figure 4. Dragging feedback tab reveals error massage.

Types of Physical Action

Purposeful actions and gestures

Participants in both CD and ID conditions used many pointing gestures to indicate a particular place on the map or a specific stamp on the table. We observed that people used more pointing gestures in the CD condition than in the ID condition. When one participant attempted to create a unit at a particular place on the map, they often informed the other participant through verbal sentences with a pointing gesture.

[No role. Relationship: Strangers]
P1: let's do (here) [Pointing to a pace on the grass].
P2: yes! [Pointing to the same place].

We found there were several factors that might simulate people to use pointing gestures. The most important factor was the use of impact tool. The impact tool was a functional stamp designed to provide users with the current world state. It was common for participants to point to each category in the impact tool when discussing their strategies. Pairs used the impact tool 62 times in the CD condition, while it was only used 39 times in the ID condition, which influenced the levels of pointing gestures.

The second primary use of the pointing gestures in the activity was to indicate a particular place on the map. Both conditions incorporated this type of use. Participants often used it when giving suggestions or discussing strategies.

However, it is important to note that more types of purposeful gestures emerged in the ID condition. For example, participants managed and sorted stamps together. These gestures related more to organizing tools than doing the activity. In contrast, the role configuration in the CD condition kept tools organized, which helped participants to focus on conducting tasks.

Contents sharing through tools

In the system, the impact and information tools provide a freezing screen feature whereby all other functions are inactive when these stamps are in use.

It is important to note that people started to concentrate on the same content and discussed their strategies when using the impact and information tools. We infer that the freezing feature might provide external tensions that force people to share group awareness.

Conflict uses of tools and space

We observed conflicting uses of tools in both CD and ID conditions, but the types of conflicts were completely different. In the ID condition, players reached for the same stamp by accident. When they realized it, they usually let the other to use it first. We suggest that this is due to a strong social constraint in adults about not taking objects out of another person's hands (as found in [24]). However, in the CD condition, when one group turned their collaboration into competition, we observed them intentionally stealing the other's tools and using them as a part of their task.

[P5 is the natural resource planner and P6 is the developer. Relationship: Friends]
P6: My job is to destroy the world. You see.
P5: I don't want you to build the factories here [holding the eraser tool to erase factories]. Why not (to do something else)?
P6: That's the point! This game for me is to create the pollution. Ha-ha!
P5: No! You destroy the world!
P6: I really want to do this [directly picking up P5's lumber stamp to use it].

Conflict use of space only occurred during parallel work in the ID condition. We noticed that sometimes the two participants would use their stamps at the same place on the map or their actions would impact the other's actions. For example, when one participant (P2) was creating houses (lumber->house) and the other participant (P1) was creating gardens (irrigation->garden) in the ID condition, they had some conflict over use of space on the map.

[No role. Relationship: Strangers]
P2: [Creates a house very close the irrigation].
P1: [Keeps trying to stamp the garden, but fails]
P1: Sorry. It is too close to (my irrigation)[pointing to the house that P1 just created]. Where is the eraser tool? I have to erase (it).
P2: Okay. It doesn't matter.
P1: You can build it here [pointing to another place which is a little bit offset from the original place].

We found that the conflict over use of space was an effective trigger point for people to switch from parallel work to collaborative or cooperative modes. It significantly encouraged people to start verbal negotiation and physical interaction.

Interactional Patterns

There was a significant difference in the interactional patterns between the CD and ID conditions. We identified four main patterns: (a) collaboration with shared goals and co-dependent uses of tools; (b) collaboration with shared goals but with only one person executing actions; (c) cooperation with separate sub-tasks and parallel uses of tools; and (d) no collaboration or cooperation with parallel uses of tools.

Co-dependent condition

The dominant interactional pattern in the CD condition was collaboration with co-dependent use of tools. In this case, participants discussed and performed the task together. Five of six groups adopted this strategy during the whole process.

Similar behaviors were found in the five groups that adopted the actively collaborative pattern. They first talked with each other about *which* units they wanted to create, *why* they had to create them as well as *how* or *where* to build on the map. Then each participant manipulated their own stamp to successfully create a specific unit.

[P4 is the natural resource planner and P3 is the developer. Relationship: Friends]
P4: No people have shelter. Oh, we don't have shelter [Looking for and picking up the lumber stamp]. Oh my god!
P3: [Laughing].
P4: Where do they want to live? [Looking for the specific place on the map]. I think in the forest. Not here [pointing to the hydro dam] because we have [a] dam.
P4: First we need to do this (create lumber)[pointing to the lumber on the map] and then?
P3: Yeah. It's basically this (single house) takes one lumber [holding the single house stamp]. This (townhouse) takes two lumbers [holding the town house stamp] and this (apartment) takes three lumbers [holding the apartment stamp].

Rather than actively discussing strategies, we observed that participants in one group (out of six) *only* asked for basic help from each other in order to complete their stamping actions during the whole activity.

[P11 is the natural resource planner and P12 is the developer. Relationship: Strangers. They did not have any conversation for almost three minutes before the following talk]
P11: Oh, I can't have a farm because I need two these (irrigations).
P12: You need more these irrigations?
P11: Yes.
P12: [Stamping two irrigations for P12].

Another interesting observation in the CD condition was that in one group, one participant stole tools from the other during the activity, which caused conflicting uses of tools for a while. The P6 who acted as the developer stole tools from the P5 who was the natural resource planner. However, the independent uses of tool did not really lead to subsequent parallel work. They still continued to verbally argue and negotiate with each other.

Independent condition

Compared to the CD condition, there was no single dominant interactional pattern in the ID condition. Participants appeared to adjust their interactional patterns from time to time. In general, we observed three patterns in the ID condition. In the first pattern, pairs cooperated to perform tasks with parallel uses of tools. They first broke down the task and assigned different sub-tasks to each person. Then each person focused on his or her own part with parallel uses of tools, to achieve their shared goals. We observed this pattern in two groups.

[No role. Relationship: Strangers]
P1: Let's do houses here [pointing to a place close to forests].
P2: We are going to cut these trees [holding both lumber and house stamps to create a single house].
P1: I will sow some more gardens [picking up both irrigation and garden stamps to build gardens].

A second pattern involved pairs working in parallel but not coordinating their activity beforehand. The independent use of tools made it possible for each person to concentrate his/her own subtasks. In one group, participants worked individually with little verbal or physical interaction during the whole activity.

A third pattern involved one person physically controlling and using the stamps, while the other person passively watched or offered verbal suggestions. Both participants were involved in verbal collaboration, but only one participant physically manipulated tools and executed tasks. Two (out of six) groups interacted this way many times in their collaboration.

In the ID condition, most groups had two or three interactional patterns, with one dominant pattern. They switched between patterns several times during the activity. Based on observation, we found three possible motivations for their switches: (a) conflicting use of space on the map; (b) frozen screen; and (c) familiarity with the system and activity.

Post-interviews: experiences between two conditions

In our post-interviews (*How do you think the different set-ups impacted your collaboration?*), we found that groups had various responses regarding the CD and ID conditions. On one hand, one group reported that they really enjoyed learning together in the CD condition. They also indicated that the co-independent use of tool made them feel like a team. On the other hand, two groups reported that they preferred the independent use of tools because it made their collaborative work more efficient and gave them more freedom to explore different tools. Three groups mentioned that they preferred to use the CD condition at the early stage to learn the activity. They said that after becoming familiar with the activity, they would like to switch to the ID condition because it gave them more freedom and ability to explore.

LIMITATION

We do not make strong claims in this study because our methodology and experiment have limitations. We have a small number of participants, which limit our ability to generalize results. Four groups of pairs knew each other prior to the study, while two groups of pairs were strangers. This difference likely also influenced collaboration.

In addition, our demographic data indicated that people had different experiences using tangible and multi-touch technologies. Although participants were given time to explore the system and familiarize themselves with it, we found there was still a learning curve for a few participants, particularly those who had never used tangible systems before. These unbalanced skills might have contributed to inequitable participation. Due to time constraints, we did not explicitly count participants' different types of physical gestures. Also, there was no inter-rater to code the video data of each participant's physical interaction.

DISCUSSION

Our goals were to understand *whether* co-dependent access points enabled more effective collaboration in terms of levels of negotiation and equity of participation than independent access points, and *how* co-dependent and independent access points supported different patterns of interaction. Our results provide some evidence that a design strategy of using co-dependent access points with tangible objects on a multi-touch tabletop encouraged more equitable verbal participation and physical interaction compared to independent access points. However, we also noticed that the independent use of tools did not always lead to parallel work. Instead, a variety of interactional patterns emerged with the independent use of tools. The analysis of video, observational and interview data led us to suggest three design considerations of importance that can be used to guide future design of collaborative tangible tabletop user interfaces.

Equitable Participation: Co-independent Access Points

In general, co-dependent access points can be designed to encourage more *equitable participation* for both verbal negotiation and physical interaction between participants. Our results are similar to previous findings presented by Roger*s et. al*. [20]. The approach would be particularly important in collaborative learning contexts. When designing tangible learning environments that require each participant to be actively involved in an activity, co-dependent access points might be considered to encourage equitable participation.

Flexible Interaction: Independent Access Points

We hypothesized that people would work independently without collaborating in the ID condition. Our results indicated that some pairs did work in parallel without much collaboration in the ID condition. However, pairs with independent access points in the ID condition also had other interactional patterns, such as cooperation involving splitting up work into separate tasks. Therefore, the ID condition is more open to different approaches.

Multiple Modes of Interaction

Our post-interview revealed that people might participate with different patterns of interaction at different points in the task. At the beginning, people may need to learn and explore the system together so that they can also learn from each other, accelerating their learning process. However, as people become familiar with the system and tools, they may want to interact in a more flexible way depending on their ideas, personalities and strategies. The system supports both modes of interaction – only the preliminary assignment of tools differed between the groups. Our approach, which encourages collaboration, in conjunction with variable instructions, may be more flexible than hard coding tool assignment in ways that enforce collaboration.

For example, at the beginning of a session, participants may be instructed (by a facilitator, teacher or the system) to take on roles to support the CD mode and encourage equitable learning participation. Later on in the session, participants could be enabled to drop their roles and switch to the ID mode to enable flexible interaction. However, if collaboration is desired, then the CD mode can remain intact for the duration of the task to avoid potential parallel work without collaboration [22,13].

Freezing Screen with Shared information

We found that our system promoted group awareness through the freezing screen feature triggered by the impact and information tools. We suggest that freezing the map screen when important information is displayed enables that information to acts as a referential anchor [4]. The map and information provide a common reference that anchors the participants' attention to a shared representation of the world state or other important information.

By disabling interaction when one participant displays important information, the other participant is encouraged to attend to that information and possibly discuss it with their partner. This enables participants to maintain a shared awareness and helps them to coordinate their subsequent interactional patterns. We observed that most times pairs employed the impact or information tools, they tended to talk and work together after they resumed interaction with the system. This observation is consistent with results from the work on a tabletop game called Futura [2].

CONCLUSION

We present the results of an exploratory study that compared the similarities and differences in collaborative behaviours of adults between the uses of co-independent and independent access points in a tangible tabletop activity. We found that co-dependent access points supported equitable verbal and physical participation compared to independent access points. It encouraged participants to discuss their goals and decisions. Independent design did not only lead to parallel interaction, it also enabled a variety of working strategies and purposeful gestures. In addition, freezing the display with informational tools encouraged subsequent collaborative behaviours. Overall, our results support the benefit of designing to support co-dependent access points. We also suggest three design recommendations for future designs of collaborative tangible tabletops.

ACNOWLEDGMENTS

Removed

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