Tool Support for Creativity using Externalizations

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ABSTRACT
Within the creativity community, researchers and practitioners have developed and studied various support tools and environments. It is important to learn from these tools and environments, identifying requirements for improving the future support of creativity in design. In this paper, we focus on support for generating and interacting with external representations to facilitate shared understanding and common ground amongst stakeholders. In considering external representations, we distinguish between artifacts provided by the tools and boundary objects created by the participants. We evaluate the use of a particular creativity support tool: the Envisionment and Discovery Collaboratory (EDC). From this evaluation we identify requirements for future tools and environments to support creative design.

Author Keywords
Creativity, Design, Externalizations, Boundary Objects, Creativity Support Tools, Design Environments, Evaluation.

ACM Classification Keywords
H.1.2 **Information Systems**: User/Machine Systems – Human factors. H.5.3 **Group and Organization Interfaces -** Computer-supported cooperative work, Evaluation/methodology.

INTRODUCTION
Many researchers and practitioners [e.g. 1, 4, 12, 16, 19] have developed tools and environments to support creativity in design. To support this creative process, externalizations such as boundary objects have received attention from both the theoretical [e.g. 2, 5, 13] and practical [e.g. 1, 4, 19] perspectives. Boundary objects are externalizations that are used to communicate and facilitate shared understanding across social, spatial, temporal, conceptual or technological gaps [7]. The use of boundary objects allows stakeholders to externalize knowledge to others within a group, facilitating the development of shared understanding and common ground [3]. Building upon the strengths and weaknesses of current tools and environments in supporting boundary objects, we wish to identify requirements for future tools and environments.

In this paper we provide an overview of support for creativity in design through current tools and environments. Refining this review further, we report an evaluation of one such tool – the Envisionment and Discovery Collaboratory (EDC) – focusing on support for boundary objects to facilitate shared understanding and common ground amongst stakeholders. We report our findings and present our requirements for the development of future creativity support tools and environments.

COMMUNITIES OF PRACTICE AND INTEREST
Design is a process that produces a new or refined product. Design is often collaborative, bringing together groups of stakeholders from diverse backgrounds to work together throughout the design process. Gennari and Reddy [10] describe the design process as 'human activity, involving communication and creative thought amongst a group of participants'. Fischer [7] describes these groups of stakeholders as Communities of Practice (CoP) and Communities of Interest (CoI). CoP are groups of stakeholders who come from the same background, sharing similar perspectives and vocabularies. CoP consist of practitioners who commonly work together (e.g. designers in a design team), whereas CoI bring together stakeholders from different CoP (e.g. designers, users, HCI specialists, programmers, etc). Design teams often consist of stakeholders who exhibit characteristics of both CoP and CoI. Design is a dynamic process [17] where stakeholders switch between different communities [13] such as user-user communities (CoP), designer-designer communities (CoP) and user-designer communities (CoI). In order to facilitate the design process it is vital to support the dynamic interaction of these various communities.

Within a CoP, the effectiveness of communication and shared understanding is aided by the stakeholders' similar backgrounds and experiences [6]. However, this can cause barriers for those outside the CoP [7, 13, 14]. Therefore, a goal for the support of design is to allow CoP to break free

of their existing perspectives and vocabularies, becoming more accessible to stakeholders from other communities.

The major challenge facing CoI in design is building shared understandings between CoP [e.g. 13-15]. Fischer [7] argues that CoP may impose barriers due to factors such as group think, suppressing exposure to and acceptance of ideas from other CoP. However, Fischer [4] further argues that breakdowns between CoP can lead to the generation of new ideas, new insights, new shared understandings, exploiting the symmetry of ignorance [5], leading to CoP establishing common ground [3]. Hence, a second goal for the support of design is to facilitate the exploitation of breakdowns as opportunities for the establishment of common ground.

The question then is: how do we facilitate these 'breakdowns as opportunities'? Fischer [5-7] has argued for providing this support through the use of boundary objects [2]. A boundary object as an artifact that talks back to the group – initiating communication amongst the group allowing shared understanding to develop, the creation of new knowledge, and critique and negotiation of this knowledge [5]. A boundary object may be considered as a conversational piece that creates and communicates knowledge, rather than a container of knowledge *per se* [7].

The externalization of stakeholders' knowledge through the use of boundary objects supports the various activities of the design process [20]: problem framing, idea generation and idea evaluation. Shared understandings can be established during problem framing by allowing stakeholders to reference boundary objects [13]. The generation of design ideas can be expressed to other CoP through the use of boundary objects, moving ideas from internal, mental conceptualizations to external, tangible, visual objects. Participants are able to create and interact with these boundary objects throughout idea generation, assisting the critique and negotiation of design ideas and decisions through the activity of idea evaluation [5]. As boundary objects evolve throughout the design process, they become more meaningful and understandable as they are discussed, used and refined, strengthening the shared understanding and common ground between CoP [9]. Boundary objects break down the barriers created by the different perspectives and vocabularies of different CoP [7], building the shared vocabularies and common ground that are crucial to the formation of CoI.

Hence, if creativity support tools and environments are effectively to support design, they should support the 'creation, dissemination and refinement of boundary objects' [4], allowing CoP to establish shared understanding and common ground as they transform the initially disparate stakeholders into a CoI.

CURRENT CREATIVITY SUPPORT TOOLS AND ENVIRONMENTS

Many researchers and practitioners have developed tools and environments to support the process of design. We describe three examples – The Envisionment and Discovery Collaboratory (EDC) [1], Caretta [19] and i-LAND [16]. Each of these environments supports the dynamic nature of design in different ways. EDC supports the design process as a group activity; Caretta supports personal and shared spaces throughout the design process; and i-LAND supports individual, sub-group and group activities in design.

The Envisionment and Discovery Collaboratory (EDC)

The EDC [4] is a computerized tool for supporting social creativity. The main goal of the EDC is to 'support social creativity by creating shared understanding among various stakeholders, contextualizing information to the task at hand, and creating objects-to-think-with in collaborative design activities' [4]. While the EDC in concept can be applied to many collaborative activities, its test bed domains have been urban design and decision-making.

Figure 1. The Envisionment and Discovery Collaboratory (EDC)

The current implementation of the EDC (Figure 1) comprises a projected image on a table, which can be manipulated via physical objects (i.e. RFID tagged wooden blocks on a grid structure embedded in the table) and an ultrasonic sketching tool, allowing boundary objects (i.e. sketches and virtual objects) to be created and evolve.

Caretta

Caretta [19] is a similar environment to the EDC, with the exception that it extends the shared interaction space to account for personal space. Caretta [19] allows stakeholders to discuss and negotiate around the shared space by manipulating physical and virtual objects, while providing the opportunity to examine ideas in their own personal spaces. Like the EDC, Caretta is applicable to many collaborative tasks, and has used the activity of urban design as its test bed.

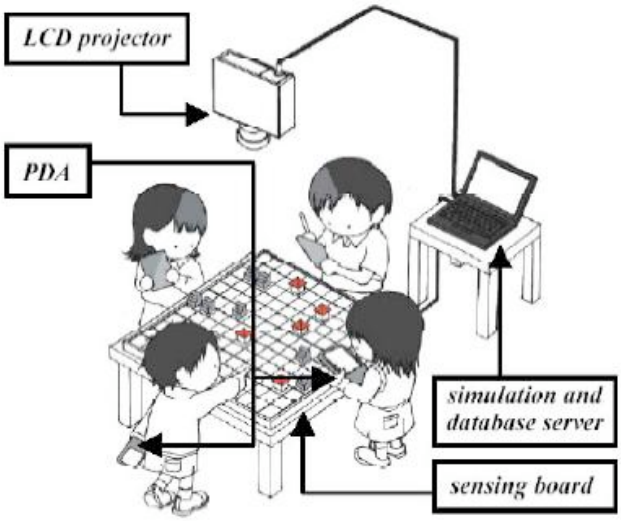

Figure 2. Caretta[1]

Caretta [19] comprises a sensing board, a simulation and database server, an LCD projector and a number of PDAs (Figure 2). The hardware exchanges data through the use of a wireless network. The shared space takes the form of a sensing board that allows users to manipulate physical objects through the use of RFID. The personal space takes the form of a PDA, which images the shared space. Upon bringing the PDA in contact with the shared space, the visualization on the PDA is updated with that of the shared space. This allows users to work in their own personal space at their own pace, while cooperatively working in the shared space and smoothly transitioning between the two.

i-LAND

The i-LAND [16] environment is a vision for future work spaces supporting the cooperative work of dynamic teams with changing needs. i-LAND achieves this through the integration of architectural and interaction spaces (i.e. integrating technologies into the meeting room environment). i-LAND has been used in the domains of brainstorming and project organization.

The i-LAND vision has been implemented through the use of several 'roomware' components [16, 18] – DynaWall, InterTable, ConnecTable and CommChair (see Figure 3). Each roomware component runs a software application for producing hypermedia concept maps using text and scribbles [16]. The use of these different roomware components provides different interaction spaces supporting the dynamics of the design team – individual, sub-group and group activities [17].

[1] Image from
Fischer, G. Domain-Oriented Design Environments: Supporting Individual and Social Creativity. *Computational Models of Creative Design IV* (1999), 83-111 with permission from Professor Gerhard Fischer

Figure 3. The i-Land Environment[2]

Meta-Analysis of Current Support Tools/Environments

As discussed above, in order to support the design process it is important to facilitate the creation, dissemination and refinement of boundary objects allowing CoP to establish shared understanding and common ground. The example environments noted here achieve this through the use of architectural and interaction spaces, allowing participants to create and interact with boundary objects, whether virtual, physical or both. The major difference between the environments is in their uses of architectural and interaction spaces.

The i-LAND environment supports three different interaction spaces: for individual work (i.e. CommChair), for sub-group activities (i.e. ConnecTable), and for work as a full group (i.e. DynaWall and InteracTable). The need for this support has been empirically shown, where groups using technologies supporting individual, sub-group and group activities achieve better results than groups working as a full-group for most of the time [17]. i-LAND was built with the vision of technologies being integrated into our existing architectural environment [16], e.g. walls, tables, chairs. However, the very act of integrating technologies into the existing architecture has created barriers between the interaction spaces. For example, a stakeholder working in the CommChair cannot be within the same interaction space as either the ConnecTable or the InteracTable, as they are constrained to the architectural space of the CommChair. Thus, particular combinations of architectural spaces and technologies impose barriers between different interaction spaces, separating CoP and potentially inhibiting the collaborative design process. How then do we overcome this problem?

Caretta [19] overcomes this problem by integrating personal and shared interaction spaces in the same architectural space. Rather than technologies being integrated into existing artifacts with established physical properties, the technologies themselves are physical objects

[2] Image from
http://www.ipsi.fraunhofer.de/ambiente/pubpics/fod.html with permission from Dr. Dr. Norbert A. Streitz

with their own set of physical properties. Due to the mobility of the PDA, the personal interaction space can be moved in and out of the architectural and interaction space of the sensing board. The disadvantage of Caretta compared to i-LAND is that no social interaction space is provided for sub-group activities. An additional problem with Caretta [19] is inherent in its implementation. Caretta [19] supports only the transition from shared space to personal space, not vice versa. Hence, an individual may go about developing an idea in her personal space, but if she wants to present the idea to other group members, she must either re-do the work in the shared space – if she can even remember how – or present her idea on the PDA. The first solution is both ineffective and time consuming, while the second is impractical due to the nature of the interaction space defined by the PDA [11]. Also, if stakeholders develop ideas in their own personal spaces, they are likely to use their personal vocabularies and perspectives. This ultimately will lead to barriers, rather than opportunities for shared understanding and common ground across the CoI.

The EDC [1] provides only a group interaction space, forcing CoI to work as a full-group. While this has been shown to inhibit the creative output of the group due to the prevention of individual and sub-group activities [17], the design of the EDC focuses on the creation of and interaction with boundary objects for developing shared understandings and common ground between CoI. While the theoretical benefits of this use of boundary objects have been described above, the question remains of their utility in practice. Evaluating a design activity using the EDC, we investigated the creation of and interaction with boundary objects and assessed their facilitation of the design process through the technological support provided by the EDC.

EVALUATION OVERVIEW

The main goal of the EDC was to 'support social creativity by creating shared understanding among various stakeholders, contextualizing information to the task at hand, and creating objects-to-think-with in collaborative design activities' [4]. We evaluated the use of external representations in the EDC to facilitate the development of shared understanding and common ground. We identified shared uses of externalizations between the CoP who participated.

METHOD

The evaluation involved groups of four participants, collaborating together to decide on the future development of land-use and the development of new bus routes, including bus stops, for the Gunbarrel area of Boulder, Colorado. Interaction with the EDC and amongst the participants was captured for post-analysis through the use of two digital video cameras and screen capture software. A questionnaire was also given to the participants after each session, assessing from a user perspective the effectiveness of the EDC in establishing shared understandings between participants.

Participants

Twenty-eight participants took part in the evaluation, forming seven groups of four. The participants varied in age from 20 to 57, with a mean of 33.25 years. All participants were from the Boulder area of Colorado, consisting of undergraduate students, postgraduate students, university staff and public sector workers. The participants were recruited from mailing lists, posters and word of mouth.

Equipment

The set up of the EDC can be seen in Figure 1. The EDC is a square table, with a projected image on the surface of the table, an embedded grid structure for detecting physical objects using RFID tags in the table, and an eBeam ultrasonic sketching tool. The input from the physical objects and the eBeam device are fed back to a standard desktop PC, which outputs the resultant graphical image via a projector on to the table surface.

The projected graphical image displays a map, a tool menu and a sketch menu, which can be manipulated via the physical objects and the eBeam sketch tool. The tool menu, which was controlled via the Admin block (see below) allowed the user to select from three options: view a satellite image of the Gunbarrel area of Boulder (i.e. Aerial option); view a road map of the area (i.e. Map option); and a Hide option which toggled through the options of land use colouring being shown or hidden. The sketch menu, which was controlled via the ultrasonic pen, allowed the users to sketch on the map. When a new sketch was created, the user had the option to: minimise the sketch; bring the sketch to the top (if multiple sketches were present); and close the sketch. There was also a colour palette projected on the table, which allowed the users to choose a line colour and a fill colour using the ultrasonic pen. In addition to this, there was an erase option, which could be selected using the ultrasonic pen, which then allowed the users to select lines and filled shapes with the ultrasonic pen to erase them.

The embedded grid structure in the table was used to detect the position of eight RFID blocks. Each RFID block had a different function as part of a pre-defined notation provided by the EDC:

1. Admin – This was a selection block to be used on the tool menu. This block was used to change between the aerial, map and hide options.
2. Single-family residential (Yellow) – This block placed a yellow square in the cell in which it was positioned on the map, indicating low-density housing, e.g. detached housing.
3. Multi-family residential (Orange) – This block placed an orange square in the cell in which it was positioned on the map, indicating high-density housing, e.g. apartments.

4. Agricultural (Brown) – This block placed a brown square in the cell in which it was positioned on the map, indicating farmland.
5. Light industrial (Blue) – This block placed a blue square in the cell in which it was positioned on the map, indicating warehouses and small factories.
6. Commercial (Red) – This block placed a red square in the cell in which it was positioned on the map, indicating shops and offices.
7. Open Space/Parks (Green) – This block placed a green square in the cell in which it was positioned on the map, indicating open land suitable for walking, playing and relaxing.
8. Remove – This block removed a land-use type (blocks 2-7) and reset it to neutral, by placing the block on the cell representing an existing land-use type.

During the evaluation, one digital video camera captured a view looking down on the EDC, observing the users' interactions with the EDC. A second digital video camera captured a wide view of the EDC and the participants, capturing data that may have been missed by the other camera. In addition to the video cameras, Camtasia screen capture software captured the screen images of the EDC.

A notebook computer was also used to play a set of audio instructions to the participants before the evaluation started.

Procedure

Participants were run in randomly assigned groups of four. Upon each participant signing a consent form to participate in the evaluation, the participants were asked to sit around the EDC while the pre-recorded instructions were played. (Participants could be seated or stand during the evaluation.) Pre-recorded instructions were used to avoid any bias between the groups. The pre-recordings gave an overview of the evaluation; an introduction to the EDC and its functionality; a practice task; and a description of the evaluation activity. After each audio file the evaluator asked the participants if they had any questions and answered them to the best of his ability. It was emphasised to the participants that we were evaluating the EDC and not the users.

The functionality of the EDC was described to the participants via an audio recording. While the audio recording was playing, the evaluator synchronously demonstrated the described functionality, so the participants were provided with an audio and visual demonstration of the available functionality. A list of the available functionality was also available on the wall next to the EDC and could be referred to by the participants at any time during the evaluation.

All participants engaged in a practice session. The evaluator read aloud the tasks one at a time from a script. When the participants completed a task, the evaluator moved on to the next task, until all the practice tasks were complete. The evaluator did not intervene during this process. If one person was confused about a particular task, the other participants in the group helped to clarify it.

After the participants had completed the practice tasks, the evaluator randomly handed each participant a slip of paper which had a role play description, which they were asked to read in private. We did not have access to 'real' users to collaborate on an urban transportation and development activity, and surrogate users often lack motivation to engage in such a task as it is not a personally meaningful activity [8]. Therefore role-play scripts were used to inform semi-authentic users. The use of these role play scripts increased the user's motivation as it made the activity more meaningful and promoted the 'symmetry of ignorance' [5]. While the participants were not 'real' users, they all lived in Boulder, Colorado and the surrounding area. The issue of the future development of the Gunbarrell area of Boulder was a very real issue to the participants.

Before the evaluation activity was presented to the participants, the evaluator loaded the EDC image file as a starting point for the evaluation. The image file contained a pre-defined map with land-use types marked up, and sketches displayed of an existing bus route and bus stops in the Gunbarrel area of Boulder.

Once all participants had read their role-play scripts, the evaluator played the evaluation activity description:

You are a group consisting of 2 residents, 1 developer and 1 city planner. You have come together to discuss the future development of the Gunbarrel area in Boulder.

Resident (R1) – You live in the southwest area of Gunbarrel. One of the reasons for you moving to this area was its location near the countryside. However, the area in which you live is a new residential development. As yet the local bus route does not serve your area, which makes getting into Boulder and to your place of work in the northwest difficult. You would like to see the bus route extended to your area to meet your transportation needs.

Resident (R2) – You live in the northeast area of Gunbarrel. You enjoy taking your dog for a daily walk in the local farmland. However, for a long time now you have been unhappy with the position of the bus stop outside your house. This causes your dog to bark when people are waiting for the bus and are getting off the bus, causing disruption to yourself and your neighbors. You would like to see the bus stop moved for a more peaceful life.

Developer – Due to an increasing demand for residential, industrial and commercial property, you are looking to buy as much land as possible to meet the growing demands – any open space and agricultural land has the potential for development. You wish these new developments to tie into the existing infrastructure and have good transportation links into Boulder.

City Planner – You wish to have developments to increase the economy in Boulder. You realize the current bus route is old and inadequate, but areas, which are not served by the current bus route, do not have a high enough demand, therefore costs cannot be justified. You wish the bus route or routes to serve the most highly populated areas for maximum profit. You also wish to position bus stops along the bus route or routes to best serve the Gunbarrel community.

The activities for the group are as follows:

1) Discuss and come up with ideas for the future development for the Gunbarrel area of Boulder – both land-type and transportation. You have an upper limit of 30 minutes for this task, unless the group finishes sooner and are happy.

2) From the ideas generated in task 1, discuss between the group members and come up with a final solution for the future development of Boulder. You have an upper limit of 10 minutes for this task, unless the group finishes sooner and are happy.

Please engage in your role playing scripts as much as possible, using the information provided and your own personal opinions and experience.

When the evaluator had dealt with all questions, the cameras were set to record and the evaluation activity began. The evaluator sat at a distance from the EDC, and reminded the participants after 30 minutes that they had 10 minutes left and should work towards a final solution if they had not already begun to do so. After 40 minutes the evaluator informed the participants that their time was up and asked them to draw to a conclusion. While it may be argued that 40 minutes was not long enough to observe the complete design process, the study did take a snapshot of design, including iterating several times through the various activities of the design process [20]. All seven groups adequately finished the activity, specifying land developments and a new bus route including bus stops, with an average time of 37.36 minutes. At the end of each session, the participants were asked to complete a questionnaire about the EDC.

FINDINGS

The findings reported in this paper are based on an analysis of the video footage and the post-evaluation questionnaires. Interactions amongst the group members were coded into four categories: verbal communication, interactions with EDC artifacts (e.g. pre-defined externalizations such as existing land type regions), the creation of boundary objects (e.g. externalizations created using the sketch tool or the RFID blocks), and interactions with boundary objects. We refer to EDC artifacts and boundary objects collectively as externalizations.

The occurrences of these interactions were analyzed across the core activities of the creative design process: problem framing, idea generation and idea evaluation [20]. Through our analysis of the video footage, 'idea generation' was refined to include: new ideas, refined ideas and combined ideas. Other activities were also observed: repeated ideas – the repetition of an idea that had already been externalized; removed ideas – the removal of an externalized idea; and, other – miscellaneous interactions (e.g. a request for an RFID block). In subsequent iterations of our analysis we focused on the three core activities of the creative process and the sub-activities of idea generation:

- *Problem Framing:* An activity of the design process in which the group clarifies the problem and develops an understanding of it, framing criteria for potential solutions to the problem. This stage may involve gathering relevant data about a problem and reviewing it.
- *Idea Generation:* An activity of the design process in which a member of the group, a sub-group or the entire group generate design decisions as a potential solution to the problem.
    - *New Idea:* The generation of a design decision that has not yet been expressed.
    - *Refined Idea:* The generation of a design decision that extends an existing design decision.
    - *Combined Idea:* The generation of a design decision from two or more existing design decisions.
- *Idea Evaluation:* An activity of the design process in which a member of the group, a sub-group or the entire group assess design decisions as a potential solution to the problem against some criteria.

Table 1 presents the mean (and SD) proportions of the four types of interactions (verbal communication, interaction with EDC artifacts, creation of boundary objects, and interaction with boundary objects) for each of the various activities of the design process, as described above.

Problem Framing

In the problem framing activity of the design process, verbal communication was the primary form of interaction (61.86% of interactions), while interacting with EDC artifacts was a major contributor of interactions (28.87%) acting as a secondary form of communication. The interactions with EDC artifacts complemented the verbal interactions between participants, providing context for the problem grounded in the EDC. For example, a common occurrence across all the groups was the residents informing the others in the group where they lived. This was achieved by pointing to their house on the map and verbally communicating to the group, 'I live here'. Without the EDC, this simple communication would have been

	% of Verbal Communication	% of Interaction with EDC Artifacts	% of Creation of Boundary Objects	% of Interaction with Boundary Objects
Problem Framing	61.86 (4.37)	28.87 (3.53)	0.42 (0.40)	8.85 (2.95)
Idea Generation	39.07 (3.77)	31.67 (6.21)	23.48 (7.89)	5.77 (3.47)
New Ideas	*36.50 (3.99)*	*32.17 (7.52)*	*26.93 (7.32)*	*4.40 (3.94)*
Refined Ideas	*45.14 (12.59)*	*27.91 (13.08)*	*18.64 (9.98)*	*8.32 (4.24)*
Combined Ideas	*50.00 (0.00)*	*0.00 (0.00)*	*0.00 (0.00)*	*50.00 (0.00)*
Idea Evaluation	58.67 (7.22)	31.60 (6.59)	0.00 (0.00)	9.74 (5.76)

Table 1. Mean (and SD) percentages for the types of interactions for various activities of the design process

considerably more complicated and prone to misunderstanding.

It is interesting to note that only one interaction (0.42%) during problem framing was due to the creation of a boundary object. This occurrence involved a participant using the sketch tool to show others "her area" on the map using her own notation. This raises the question: why did participants not create boundary objects to develop shared understandings during problem framing? In the example noted, while one participant claimed that such information was valuable, the group decided to remove the boundary object to avoid confusion as it did not fit into the existing notation with which they were working (i.e. open spaces denoted as green areas, commercial spaces denoted as red areas, etc). It may be the case that the pre-defined notation used by the EDC (i.e. EDC artifacts) constrained stakeholders' expressions of boundary objects. In the questionnaire, participants commented that 'the EDC is rigid in its functionality; no room for altering methods to fit learning needs' and 'it felt like we really had to work around some of the aspects to get what we wanted'. Moving away from pre-defined notations would allow stakeholders to develop their own notations suitable for the group and the problem at hand. However, it should be acknowledged that pre-defined notations provide a certain amount of support for users (e.g. a framework to work within). There is an obvious trade-off between the rigidness and flexibility provided by a creativity support tool.

Boundary objects saw their second highest occurrence of use during the problem-framing phase of the creative process (8.85% of interactions). This accounted for 23.47% of all interactions with externalizations. One possible explanation for the reduced interactions with boundary objects compared to EDC artifacts was participants focused more on framing the context of the problem. It was very common for participants to ask questions such as, 'What is this land type again?' Allowing participants to create such artifacts may have increased their shared understanding of the context of the problem, reducing the need for phases of problem framing when interacting with EDC artifacts. There is a trade-off here between system-defined contexts (i.e. EDC artifacts) and developed shared understandings.

Across all the groups, participants used interactions with externalizations to extend communication with the group beyond their verbal communication. When participants interacted with externalizations (e.g. informing others of the current bus route), they typically continued the physical interaction after they had stopped their verbal communication to the group. While this gave others within the group the opportunity to express themselves verbally, the interaction with externalizations acted as a secondary communication medium. Participants also frequently interacted with externalizations before beginning their verbal communication, informing the group of something they wished to talk about. This use of interactions with externalizations allowed participants to extend their communication with the group, transitioning smoothly from a secondary to the more prominent primary (verbal) form of communication.

Through the use of externalizations in problem framing, a more concrete understanding was developed amongst participants. In the questionnaire, participants commented that the EDC allowed people's different perspectives to be expressed, which in turn facilitated shared understanding. As time progressed, stronger shared understandings developed, increasing the number of ideas generated and the productivity of the group, as predicted by Fischer and Ostwald [9]. The externalizations went beyond being a complement to verbal communication to being a necessity in creating a shared understanding of the problem that eventually led to the development of potential solutions.

Idea Generation

The idea generation activity of the design process saw much more of an equal distribution of interaction types. Verbal communication accounted for 39.07% of interactions, while interactions with EDC artifacts accounted for 31.67%. The creation of boundary objects saw its highest frequency of use (23.48%) throughout the creative process, while interactions with boundary objects saw its lowest occurrence throughout the creative design process (5.77%).

In the phase of idea generation, when participants verbally expressed an idea they also acted out their idea or, in the case of an already existing idea, emphasized their idea by interacting with the externalizations. Interacting with these

boundary objects added context, facilitating greater shared understanding. For example, if a participant added a bus route, the participant would then interact with the bus route to depict the route the bus would follow. Such interactions provide a new level of information to other members of the group. However, when these interactions stopped, the context was lost. This sometimes led to participants asking for problem framing information later in the design process regarding the context of these lost interactions. If a support tool could capture these interactions with externalizations, this contextual information would not be lost.

New Ideas: When a participant wanted to express a new idea she typically did so by first interacting with the EDC to act out her idea. For a bus route, for example, this involved drawing an imaginary line with a finger. For describing a possible residential development, it involved delineating the intended area with a finger or hand. This form of interaction acted as a 'dry run' – conveying information while not changing the shared solution space. Others within the group would then give their agreement to drawing the idea, usually using the EDC sketch tool. This led to a shared understanding of the idea, which allowed the group to establish a deeper understanding (i.e. problem framing), or to evaluate the idea in context (i.e. idea evaluation). However, some ideas were never verbally communicated and boundary objects were just created. For example, a group was discussing the roads in a particular area of the map (i.e. problem framing). Suddenly, one participant grabbed the EDC sketch tool and drew a potential bus route without prior discussion with the rest of the group. This was considered more of a 'wet run'. In either case, the 'dry' or 'wet' run of idea generation, the interaction with externalizations or creation of a boundary object was essential to the dissemination of the idea, leading to the group iterating through activities of problem framing and idea evaluation.

Refined Ideas: In contrast to the process of creating new ideas, the refinement of ideas involved much more purely verbal communication (45.14%). Instead of manipulating the boundary object representing the idea, participants typically talked around the existing boundary objects, verbally expressing their ideas and interacting with the existing boundary objects (8.32% of interactions for refined ideas), acting out their refinement of the idea. Extending our analysis of the data for each group to new and refined ideas, we find that boundary objects were created for only 46.36% (39.01) of refined ideas, whereas boundary objects were created for 75.26% (24.24) of new ideas. While refinement was a more verbal process, the creation of boundary objects was often used *post hoc* to summarize the refinement.

Four of the groups generated more new ideas than refined ideas (ratio 11:4). While the other three groups refined more ideas compared to generating new ideas (ratio 5:4). An important observation here is that different groups adopted different preferences for idea generation, whether it was generating many new ideas, or generating a smaller set of new ideas and refining them. It is therefore important that the technological support must be open to supporting the way the group wishes to work.

Combined Ideas: Combination of ideas was very rare in the observed design activity. In fact, only 2 ideas were combined across all seven groups. As is reflected in Table 1, combining ideas did not require the creation of a boundary object, as they already existed in the EDC as representations of previously generated ideas. Participants simply interacted with the existing boundary objects and verbally communicated with the group about their ideas.

We further extended our analysis to include *repeated and removed ideas*. We consider repeated ideas and removed ideas together as they are related in the idea generation process. The generation of ideas involved a great deal of trial and error. Participants noted in the questionnaire that the EDC allowed participants to make rapid changes without committing to them and to collaborate around these ideas. This led to many boundary objects being created, evaluated and then abandoned so that other ideas could be tried and tested. Just under half the boundary objects created (sketches – 46.12%; blocks – 42.58%) were removed. However, when participants revisited previous ideas, boundary objects had to be re-drawn (sketches - 19.04%; blocks – 9.16%). Multiple views could have supported the development of these ideas without the need to remove boundary objects, further supporting the exploratory process of idea generation.

The sub-activities of idea generation were facilitated by the EDC using the ultrasonic sketch tool and the RFID blocks. 80% of boundary objects created during idea generation were created using the sketch tool, while the other 20% were created using the RFID blocks. Participants described the sketch tool in the questionnaire as 'crucial' for the development of ideas. The sketch tool gained favor with participants due to its flexibility. The sketch tool gave the participants the ability to manipulate boundary objects as they wished, whereas the RFID blocks were constrained to a grid structure and pre-defined colors. Hence, the virtual representations of boundary objects were constrained by the physical objects that manipulated them. However, an interesting observation was that one participant (a developer) who was dominant throughout the design activity preferred the RFID blocks due to their imposing nature. Sketches could be minimized and easily erased, whereas the RFID blocks acted on a single layer that was always visible. This constrained others in the group, reducing their abilities to express their ideas, but appealed to this participant, giving her greater control over the development of the final solution. We see here how the EDC provides support for constrained and structured approach to the externalization of ideas using the RFID blocks, while the sketch tool provided the users with flexibility to create and manipulate the externalizations the way they wished.

During the idea generation activity of design, externalizations facilitated the exploration of ideas between members of the group. The creation of boundary objects had its most dominant role in this activity of the design process, allowing ideas to be shaped ready for evaluation.

Idea Evaluation

As in the problem framing activity of the design process, the idea evaluation activity involved verbal communication as its primary form of interaction (58.67% of interactions). This was once again frequently complemented through the use of interactions with externalizations acting as a secondary form of communication (31.90%). Interaction with boundary objects saw its highest frequency (9.74%).

Idea evaluation focused around the boundary objects created in the idea generation activity and the context (i.e. EDC artifacts) in which they were situated. The idea evaluation activity was heavily reliant on interactions with these externalizations identifying to others in the group what a participant was critiquing. The ease of reference provided by the externalizations facilitated the evaluation of ideas. For example, a participant followed a bus route with his finger, assessing the positioning of bus stops along the route based on the location of junctions along the route. Without the boundary object (i.e. the bus route representation) and the situation of the boundary object in its context (i.e. the EDC's representation of the map of the Gunbarrel area), this idea evaluation activity would have been much less efficient and effective.

Participants evaluated boundary objects against surrounding EDC artifacts, rather than directly comparing alternative ideas represented as boundary objects for the same purpose in the same context. For example, they would compare one or more proposed bus routes independently against other features of the map but would not directly compare two or more potential bus routes. This is one reason for the high occurrence of interactions with EDC artifacts compared to boundary objects. This way of evaluating boundary objects was a result of the EDC constraining the solution space to a single instantiation. As we saw with the removal and recreation of ideas in the idea generation activity, the idea evaluation activity also involved considerable trial and error. A stakeholder presented an idea that was evaluated, leading to another stakeholder presenting an idea that was then evaluated. If participants wished to go back to considering a previous idea, it required the removal of the boundary object representing the current idea and the recreation of the previous idea. This process continued until agreement was reached within the group. Multiple instantiations of the solution space could have facilitated the comparison of ideas, reducing the need for boundary objects to be removed and recreated – the exploration of ideas, rather than trial and error.

Similar to the problem framing activity, the creation of boundary objects was not observed in the idea evaluation activity. Participants evaluated ideas by interacting with existing boundary objects representing the ideas and surrounding EDC artifacts that may be related (e.g. evaluating the position of the bus stop based on surrounding developments). Once again, these interactions had the benefit of adding contextual information to the boundary object. Again, however, when the interactions stopped, the context was also lost, often leading to later repetition of this information. The capture of these interactions through contextual boundary objects would mitigate the loss of knowledge and context. However, this could clutter and even corrupt the solution space stakeholders are trying to evaluate. Providing separate spaces for idea evaluation, as also suggested for problem framing, could facilitate the creation of boundary objects to facilitate shared understanding in idea evaluation.

Through idea evaluation, shared understandings were further developed and refined, iterating through activities of problem framing. In addition, this shared understanding and evaluation process promoted the creation, dissemination and refinement of ideas through the idea generation activity. The use of externalizations facilitated the iteration inherent in the design process by providing a shared resource that bridged the various activities of problem framing, idea generation and idea evaluation.

CONCLUSIONS AND FUTURE WORK

In this paper, we have explored the use of externalizations provided by technological support tools to facilitate shared understandings and common ground in design activities. Our study showed externalizations to be an essential part of the EDC's facilitation of various activities in the design process: problem framing, idea generation and idea evaluation [20]. Interactions with the EDC artifacts and the context it provided were very important to the use, while the use of boundary objects was embedded in this context. The creation of boundary objects allowed ideas to move from mental representations to visual, tangible objects and facilitated critique and negotiation of these ideas. Interactions with externalizations facilitated shared understanding amongst stakeholders, adding detail beyond that provided through verbal communication.

From our study we identified requirements that should be addressed in the future development of the EDC and other support tools and environments in order effectively to support creative design through the use of externalizations:

Requirement 1: Facilitate stakeholder control of the creation of boundary objects and their notation. In the EDC, the sketch tool allowed the participants to form ambiguous shapes whereas the RFID blocks were constrained to the embedded grid structure. The sketch tool provided a rich color palette, whereas the RFID blocks were constrained to a few pre-defined colors. We recommend the use of free-hand drawing tools that can be applied to the creation of boundary objects.

Requirement 2: Allow stakeholders to capture their interactions with boundary objects. Stakeholders used interactions with boundary objects to convey information beyond that expressed verbally. However, when these interactions stopped, the information carried by them was lost. This frequently resulted in the repetition of this information. We recommend capturing these interactions, for example through the use of annotations or simple animations.

Requirement 3: Provide stakeholders with different kinds of spaces for the creation of boundary objects. The EDC provides stakeholders with one space in which to work – the solution space. The creation of boundary objects outside the scope of the solution (e.g. problem framing) leads to confusion and clutters the solution space itself. We recommend the use of separate spaces for the creation of boundary objects for different purposes such as problem framing, idea generation and idea evaluation, but also support for the seamless transition between these spaces.

Requirement 4: Provide stakeholders with multiple instantiations of the solution space. The provision of a single solution space frequently led to the removal and subsequent repetition of ideas. We recommend allowing stakeholders to create multiple instantiations of the solution space to allow for the comparison of boundary objects representing different potential solutions.

Through integrating these requirements into future creativity support tools and environments and building upon them we can look towards improving the creative practices of design and the products of the design process.

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