MakeAware: Designing to Support Situation Awareness in Makerspaces

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ABSTRACT
People new to making and makerspaces often struggle with identifying what tools are available and where they are, understanding how to operate the tools, and predicting how their decisions will affect their final product. From literature on novices and our interviews with expert makers, we identified situation awareness support as one possible way to address some of the challenges faced by novices. We present a set of design goals intended to scaffold situation awareness in a makerspace, and MakeAware, a prototype system we implemented based on those design goals. MakeAware provides a combination of environmental cues, information about the project process, and background knowledge. In a preliminary evaluation, we found MakeAware can help novices make conscious choices during a project and put more emphasis on planning, thereby exhibiting traits associated with having situation awareness while making.

Author Keywords
making; situation awareness; fabrication.

CSS Concepts
• **Human-centered computing** ~ Human computer interaction (HCI) • **Human-centered computing ~ Human computer interaction (HCI)** ~ HCI theory, concepts and models • **Human-centered computing ~ Human computer interaction (HCI)** ~ Interactive systems and tools

INTRODUCTION
Making activities such as self-directed hands-on projects [11] have become increasingly popular in both the research community and public practice [2, 9, 22, 27]. Individuals with a variety of skill levels have begun to undertake making tasks using a variety of tools, materials, and techniques. In unfamiliar workshops and makerspaces, the tools and space that the makers need to use can often cause difficulties, with novice makers unaware of where tools are, how to use them, or what tools can produce a given result [1, 15]. This can cause frustration which may dissuade them from completing or even initiating making activities [12, 17]. In addition, the instructional materials that makers use are typically authored without a reference to the individual maker’s environment and therefore do not account for the tools or safety considerations of the space.

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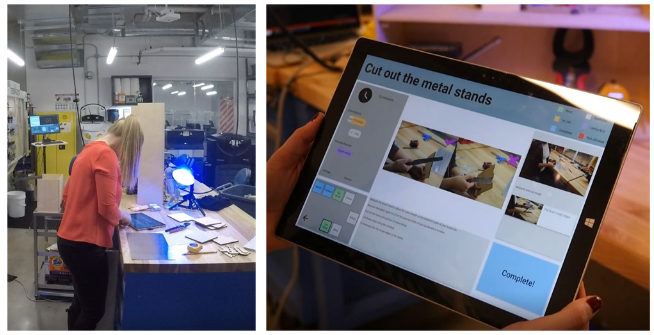

Figure 1: MakeAware helps with building artifacts using contextual (via sensors and state beacons) and process-related cues (via tablet interface).

Instructions for making typically provide a prescribed set of procedural steps to create the desired artifact [38]. As the step sequence is pre-determined, the maker is usually unsupported when they need to deviate from the instructions, do not have the skills to complete a step, or if they want to adapt a project to meet a new goal. Additionally, prescribed instructions often do not help the maker understand what the downstream effects of their actions will be [20].

To better accommodate makers' needs as they progress through a making task, we leverage the Situation Awareness (SA) framework [7, 8] and apply it to the domain of making and fabrication. Applying the SA framework to the domain of making helps the maker learn about the many elements in the environment that may influence their making process (e.g., which tools are available--*perception*), understand the meaning of the various elements (e.g., which tool is appropriate for specific tasks--*comprehension*), and predict the implications of the actions taken (e.g., know how the artifact will appear when finished--*projection*). Our design to support situation awareness for novice makers incorporates concepts from related work such as process-oriented instruction and branched documentation.

In this paper, we contribute:

- Results of interviews with expert makers which highlight how SA can benefit makers.
- Preliminary design goals to support situation awareness based on our interviews and the difficulties novices face according to related work.
- The design of MakeAware, a novel system which scaffolds situation awareness within making tasks to achieve the design goals (Figure 1).
- A discussion of the opportunities and challenges for supporting SA in makerspaces.

BACKGROUND

Situation Awareness (SA) is *"the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future"* [7]. Endsley's model of SA identifies and proposes three internalized mental levels that users encounter when performing tasks that are primarily physical or perceptual in nature [8].

Within the first level, *perception*, the user perceives "the status, attributes, and dynamics of all relevant elements in the environment". In the second level, *comprehension*, the user understands the significance of these elements in light of their goals. In the third level, *projection*, the user predicts the future status of the elements and the environment as a whole. The three levels of SA are highly intertwined and dependent upon each other, for example, *projection* cannot be achieved without also having complete awareness at the *perception* and *comprehension* levels.

SA has been commonly applied to the domain of aviation, wherein the crew must attend and respond to the dynamism of many environmental factors to make accurate decisions that have little room for error [6, 14, 26]. More recently SA has also been applied to managing 3D design courses to help teachers visualize student progress and detect and address common challenges faced by students [5]. SA has also been applied to drivers of semi-autonomous [31] and self-driving cars [25] to guide them toward safer driving decisions.

We believe Endsley's SA model can be useful in making contexts because it highlights the importance of providing individuals with information about how all the entities in their environment relate to their work context, thereby helping them form a complete picture and decreasing the likelihood of making mistakes [8]. Such information could support novice makers who might otherwise be deterred by excessive obstacles [13].

RELATED WORK

Prior research on the challenges faced by novice makers, and augmentation of procedural tasks informed this work.

Challenges for Novices in Making

Past literature has highlighted that novice makers struggle with all stages of making and fabrication [12, 15, 30]. Ludwig et al. [18], for example, found that when 3D printing, participants faced many challenges such as not being able to perceive and isolate problems with hardware and software. They also lacked an understanding of the implications of environmental factors such as how the room temperature could cause 3D prints to warp. They thus recommended that to help makers with framing making problems in accordance with their overall context it is essential to ensure that makers can capture all influential factors.

Other studies have highlighted how novices struggle with comprehending the meaning of ongoing processes and changing variables. Knibbe et al. [15] found that although novice makers paid attention to individual steps within a set of instructions, they did not comprehend the wider goal. This made it difficult to resolve issues that arose or identify potential shortcuts to save time while making. Both Knibbe et al. [15] and Hudson et al. [12] also identified that novices often use a single tool to complete multiple tasks, even if it is not the correct tool to do so.

Novices were also found to struggle with predicting the future status or outcome of a project. Hudson et al. [12] and Annett et al. [1] found that novice makers often do not predict the future implications of a design decision, and begin modelling right away. This results in the makers having to undertake more corrective measures.

Augmenting Procedural Tasks

Prior research has proposed various software and hardware tools that provide environmental and process-related cues to support procedural tasks such as learning [24], cooking ([4, 13, 20]) and fabrication (e.g., [10, 15, 17, 23, 30, 34]).

One common approach to support procedural tasks includes tracking the workflow of a maker and projecting relevant information on walls [26], surfaces [13, 25], or on tools (e.g., [4, 10, 23]). "Smart" handheld tools that help with specific sub-steps in the project such as achieving accurate cuts on large-scale surfaces [21] or ensuring users stay engaged in activities such as milling [33], have also been proposed [34].

Prior systems also provide support at the instruction level. Projects such as Ambient Help [19] and Automatics [17] help users by dynamically generating knowledge resources based on the environmental context or user input. In addition, projects such as ElectroTutor [32] demonstrated test-driven tutorials, wherein the tutorial itself interjects interactive tests to help makers understand individual steps. Each of these instruction-level supports, with the exception of Automatics [17], are often specific to individual steps in the instructions and do not relate to the overarching goal of the project.

Our system is similar to more comprehensive interactive systems such as Smart Makerspace [15], a tabletop-based system that visualizes instructions for completing DIY projects. MakeAware is similar in that we also provide information about the task overview, support learning domain knowledge by watching relevant videos, and indicate the status of tools being used in the project. However, unlike the Smart Makerspace our goal is not to take a novice through a prescribed number of steps in a linear fashion similar to online tutorials such as Instructables [35]. Instead, informed by the SA framework, we provide makers with process and environment-relevant information and help them select their own methods for completing tasks.

We also draw on work by Tseng et al. who presented Build-In-Progress, an online platform where makers document their projects as a series of separate steps linked together in a tree format. This allows the creators to share different paths they explored, including successful, failed, or experimental paths. It also allows readers to view only the steps that are relevant to them, or to work through the whole project if they choose. We use a similar branched documentation idea but implemented it from the perspective of the maker who follows the instructions rather than the author.

DESIGNING FOR SITUATION AWARENESS IN MAKING

Literature sheds light on the challenges faced by novice makers. We hypothesize that novices can overcome those challenges if they receive support for gaining SA. As part of our design exploration to support novices in this way, we decided to learn more from interviewing experts who are able to *perceive* the environment, *comprehend* the process and *project* into the future implications of their decisions.

Procedure

We conducted semi-structured interviews with four experts from local makerspaces. Sessions lasted 30-45 minutes.

Our making and fabrication experts held leading and technical roles in four different makerspaces. They reported having between 3-40 years of experience (median: 8) with making, and between 2-6 years of experience teaching novice makers, either formally or informally. Overall, interviewees said they were very familiar with both additive and subtractive digital fabrication workflows.

Analysis

We applied deductive coding to analyze the interview responses [3], explicitly searching for evidence of the three SA levels (*perception, comprehension, projection*). While our sample size is small, we found repetition in the responses between participants, validating the occurrence of such interactions.

Results

In this subsection, experts will be referenced as E[number]. Some of the points below could be discussed in relation to multiple levels of SA. This is expected since the levels are highly connected. Therefore, each response as it is discussed below should be read as one example of how it fits into the SA framework.

Challenges and Techniques for Perception

Experts recognize tools and materials that could be useful for their projects. *"For example, if the laser cutter is down then I'll be on a Dremel motor saw or some other kind of saw to try to cut out the details I was looking for"* [E3]. This maker describes a situation in which they were able to *perceive* that a tool was broken, and to recognize an alternate tool.

Because of their knowledge and experience, experts are also able to *perceive* safety risks or situations where errors may occur. "*In general, I try and parcel the task into as many small pieces as I can. So, it's easy to see, once the setup is ready, this small piece will be safe or unsafe*" [E1]. This also helps them to keep novices safe since they know which tasks have an associated risk and can intervene if necessary. "*You can just look for that exact time when they slip or the machine is set wrong, and then you can stop them*." [E1]. This maker describes being able to *perceive* safety concerns involved in the task.

The ability to recognize tools is essential in overcoming obstacles such as the broken laser cutter described by E3. The ability to recognize safety risks also benefits experts like E1 who are able to prevent accidents in the makerspace. This shows two examples of how *perception* benefits experts.

Challenges and Techniques for Comprehension

Expert makers understand their project as a whole and at the level of each individual step. "*It's really easy to get swept away into these individual steps. And I find if I do that, my project drastically changes from what I had originally envisioned. So, keeping that end goal in mind is something I always remind myself*" [E3]. This expert describes *comprehending* their actions in relation to their goals.

Our experts help novices to *comprehend* their projects in a similar way. "*We provide them with notebooks so they can draw a sketch of what they want and map out a plan. That usually helps to tie them back into their project"* [E3].

This level of understanding helps experts perform their tasks correctly, because they understand how their actions will affect the overall course of their project. These examples emphasize planning and keeping track of goals as important parts of *comprehending* a project.

Challenges and Techniques for Projection

Expert makers have an increased ability to predict the results of their actions. This is evidenced by their ability to constantly adapt and refine the project while still reaching their goals when they encounter obstacles such as unavailable or broken equipment: "*There's many ways to do the same operation. So, it's just thinking creatively or critically as to how you can get the same result but using different methods. Maybe it's changing around your workflow, maybe it's using different tools*" [E2]. And as E0 said, "*Always your goal is to come up with what you want. There is no compromise. You can use your hand or any other tools or if you have to, you stop the job, repair it, and then you continue*." Both these makers describe how they *project* forward to understand how their possible actions can help them to reach their goals.

This ability to *project* and anticipate the results of their actions helps experts to overcome obstacles (e.g. missing equipment, adjusted requirements) while still understanding which actions will help them arrive at their goal.

Design Goals

Informed by our expert interviews and literature on novices, in this subsection we describe our design goals for scaffolding SA. This is not a definitive set of differences between novices and experts, but rather reflects on some common findings that were observed in our interviews and related work.

We suggest three design goals to scaffold the gaining of situation awareness for novice makers. Each goal is described below in terms of how it contributes to each of the three situation awareness levels: *perception, comprehension,* and *projection.*

[D1] **Support planning by providing information at varying levels of detail at different stages of the project.**

Planning is essential to making activities as evidenced by the described successes of our expert makers, who emphasize planning at an overarching level and during the implementation of the sub-steps. Literature has however highlighted that novices typically plan little in advance of starting a project [13, 20]. To address this issue, we suggest that systems can be designed to provide novices with project-related information at varying levels of detail. For example, the system can provide meta-level information about the project (e.g., how many steps does the project include?) throughout the process to support them *projecting* into the future to predict their project trajectory. The system can also communicate the status or conditions of the tools (e.g., where is the tool and is it available for using?) to help novices *perceive* those tool statuses while choosing which task to complete; Lastly, it can provide attributes and dynamics (e.g., how does the tool work?) so the novice can *comprehend* the use of a tool while executing a task.

[D2] **Support novices with making choices, improvising, and adapting by providing non-prescriptive project instructions.**

As mentioned by our experts, adapting and refining projects is important to achieve the end goal. To do this, makers must understand which tools and processes can provide a desired result. However, literature has highlighted that novices typically continue to use the same techniques and tools despite the outcomes [16]. To help novices improvise and adapt throughout their projects in a way similar to experts, such as customizing, avoiding or recovering from mistakes (i.e. *perceiving* potential difficulties), and selecting the best tool (i.e. *comprehending* the purpose of the tools), and to help them review these decisions in advance (i.e. to exhibit *projection*), systems can be designed to provide non-prescriptive project instructions. For example, the system can show multiple paths that a maker can take to achieve the end goal along with a list of available resources, thereby creating opportunities for them to make an informed decision about their choices based on the context.

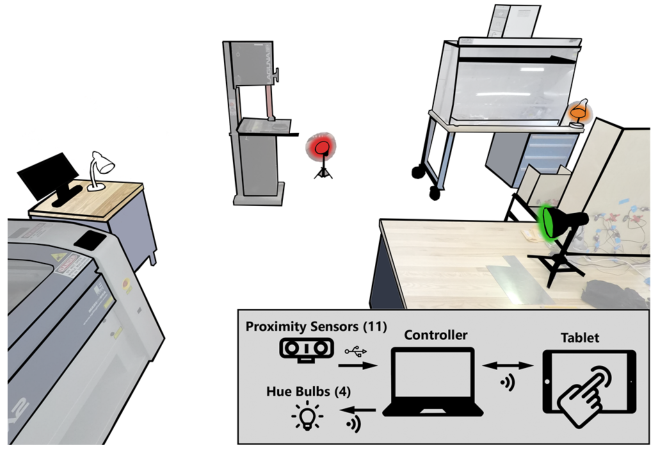

Figure 2: We set up four stations in our makerspace to evaluate MakeAware. Each station is equipped with task beacons (implemented using Hue bulbs) which bring environmental cues to the maker’s attention. The inset (bottom right) depicts the interactions between the components of the system.

[D3] **Help novices focus on subtasks while maintaining awareness of the overarching goal.**

As mentioned by experts, it is important to maintain a balance between knowing the overarching goal and focusing on the subtasks. Novices typically find this challenging [16]. To address this issue and to prevent novices from being overwhelmed by large projects, we suggest that systems can be designed to provide features that help them focus on subtasks (i.e. to *comprehend* their current activities). However, to also prevent novices from losing sight of their overarching project goal while working on subtasks, these systems should include features that support their understanding of what each subtask is for and how the result will lead into future tasks (i.e. *projection*).

MAKEAWARE

To demonstrate and evaluate our design goals, we created MakeAware, which supports novices in planning, making decisions, and maintaining awareness of their project goals.

MakeAware consists of two main parts – Tablet Interface and State Beacons – which in turn constitute individual system features. Below we describe these individual features and highlight the design goal it corresponds to, referred to as D[number], and the level of situation awareness (*perception, comprehension*, and *projection* [8]) it provides.

System Overview

Software Architecture

Makers interact with our system using a custom Tablet Interface which provides makers with information about tools and project steps, and which runs on a Microsoft Surface tablet. Additionally, IR sensors are attached to tool shelves to verify the presence of tools. The sensor values, in combination with the user’s project progress communicated from the tablet, determine the colour of the State Beacons, which are implemented using colour-changing Philips Hue bulbs distributed throughout the space. The Tablet and Beacon interfaces communicate via a central controller program on a laptop, and the sensor data is communicated to the controller via USB (Figure 2).

Tablet Interface

Overview

The overview feature is designed to support overall planning (D1) and helps with gaining the third level of SA, *projection*. The overview screen (Figure 3a) presents to the maker an overall description of the project. An image of the intended final result of the project is displayed prominently, alongside a brief text description of the project. The overview also includes a summary of the tools and materials, the difficulty level of the project, and a time estimate for completing the project based on previously available data. This information aims to provide a goal-oriented overview, which is a different approach than Smart Makerspace [15] where they provide a glimpse of each task, resulting in a task-oriented overview. Our choice to implement the goal-oriented overview is based on our expert interviews, which highlighted how losing sight of the overall goal can lead to errors and wasted time. This feature supports *projection* by helping makers to form expectations for their final product and how they might achieve it.

Project Map

The project map is designed to give makers an opportunity to learn about the options available for implementation and make decisions about how to customize and adapt the project to their needs (D2). As part of gaining this information, we expect the maker will primarily gain the second level of SA, *comprehension*.

The project map presents the individual tasks arranged as a directed acyclic graph that allows the maker to primarily *comprehend* how each task relates to the others (Figure 3c). The map shows task dependencies with solid line paths between the tasks (i.e. task A needs to be completed before task B). The map also shows optional steps (e.g., a maker may or may not want to add aesthetic decoration to their project) using dotted paths. A branching layout emphasizes that groups of tasks can be completed in any order. This is intended to support makers in choosing alternate tasks to complete if, for example, an important tool required for some task is currently in use.

Makers can complete each task in a number of ways. For example, project pieces can be attached to each other using nails, screws, or glue. To provide this information, our project map embeds buttons within each task node that indicate the methods by which the task can be completed. This can also help them to customize their project, e.g. by showing alternate decorative techniques.

Other designs could include listing alternate methods as separate optional steps in the project map rather than as options within one step. We chose our implementation to reduce complexity in the project map layout, making it easier to navigate by decreasing the number of nodes.

Each completed task is indicated by a blue coloured node and marked with a checkmark. Informed by the steps completed, all possible next steps are highlighted as green coloured nodes. We chose green because it is commonly used to tell people to proceed. The screen also includes a legend explaining the meaning of the colours. Project progress may also be able to be portrayed via symbols rather than colours, but we chose colours to achieve consistency between the tablet interface and the state beacons, described below.

Peeking

The peeking feature enables makers to get specific task details without losing sight of the overview of the tasks involved (D3), thus providing support for *comprehension* and *projection*. Peeking is implemented via a small pop-up card that makers can access by clicking the ellipsis button next to each task button. The card contains an image of what the intended final result of the task will be, as well as required tools and materials, the estimated required time, and the difficulty level of the task. Based on this information, we hope novices can make informed decisions about which task to complete first, or which method to use to complete the next task, based on their skills and available equipment rather than simply following a prescriptive order of tasks. This feature also supports D1 in that it allows the maker to view some details about each task without having to leave the project map view. Alternate designs for this feature could include adding images of each step to the project map, but we chose to implement the peeking card to include more text-based details about the task than an image could show.

Task Instructions

The task information page is similar to the overview page but provides specific details related to the task at hand and aims to support all three levels of SA, *perception*, *comprehension*, and *projection*. (Figure 3e). The instruction page contains a metadata panel which provides information about the availability of tools and materials. Currently we only track tools and not materials. All tools that are recommended to be used for that specific step are indicated in grey by default; if a tool is not present in its position on the shelf, it will be shown in orange to indicate that it is currently "in use". We chose orange as it is a commonly used colour for warnings. While this may be easily visible information for larger equipment (e.g. CNC machines), tracking tool status can be helpful when looking for smaller pieces of equipment placed on different shelves throughout the makerspace. This feature supports *perception* and *comprehension*, allowing the maker to notice if tools are unavailable. This feature supports D1 in that it helps makers to plan which tools they need and if tools are unavailable, plan alternate ways to proceed.

Similar to the overview page, the instruction page also contains an image which shows the intended final result of the step, thereby enabling *projection* which helps makers to form goals and expectations about what they should achieve.

Figure 3: A storyboard depicting one participant's progress through the project while using MakeAware. After reviewing the project overview, the participant moves to the station lit in green to begin sketching designs. They follow the steps set out in the project map to create an Illustrator template, laser cut the bookend pieces, assemble them, and document the results. Finally, they are able to review the results of each step they chose to take.

The page also contains a mini-map which summarizes the full project map to prevent the maker from losing track of the global context of their current goal (thereby continuing to support D3). Clicking on the mini-map takes the maker back to the project map page.

To provide additional support for *comprehension* and to compensate for any lack of background knowledge, we include a traditional set of written instructions for the step and a playlist of instructional videos related to the current step in the project.

If the selected task requires the use of equipment that the current maker does not have appropriate safety training for, a translucent red overlay will cover the instruction screen. Red was chosen as it is a colour commonly used to tell someone to stop. The “complete” button is also disabled, indicating that the maker cannot complete the task using the selected method; they should choose another method from the project map. However, to encourage *comprehension* and the development of background knowledge, we still allow the maker to interact with the video playlist and to view the instructions and metadata if they desire.

Progress Capture

After the maker marks a step complete, they are prompted to take a photo of their progress using the camera on the tablet. After the photo is taken, they can also add written notes to describe how they accomplished the task, including any tools, materials, or techniques not included in the existing instructions. This information is saved and can be viewed when the project is complete. The progress capture is currently used to provide a project summary, and opportunity for reflection (Figure 3i,j). In further iterations of the system, these pathways could be shared with others, fleshing out the project map with more ways in which the same project can be accomplished, any shortcuts that can be taken, as well as any advice for possible errors that may occur (D2).

State Beacons

Project and Environment State Details

State beacons are colour-changing lights that guide makers around the space and help with overall planning (D1). We believe this is a valuable feature to support *perception, comprehension*, and *projection*, since novice makers may not have the knowledge of the makerspace and the stations at which tools are available. The colours we used here are consistent with the legend on the tablet interface. State beacons are tied to the project map and turn green at stations where the next possible steps can be executed. Once the maker has selected a task they wish to complete, the beacon at the corresponding location will turn from green to blue, indicating that it is the currently selected task. Beacons at locations that do not correspond to any currently relevant tasks are white.

The state beacons also serve an additional purpose by providing information about the environment. Similar to the task instruction page, if tools are being used at a particular location, the corresponding beacon will turn orange and when the system detects a maker that does not have the safety training to use a specific piece of equipment, for example, a band saw, the beacon at the band saw will be red.

In contrast to the indicator lights used by Smart Makerspace [15], instead of highlighting only the location of a particular tool or component, MakeAware uses the embedded lights to communicate the location, as well as state information (availability, permissions, etc.) via ambient cues.

EVALUATION

To gauge the utility of MakeAware and its ability to support situation awareness in novice makers, we conducted an initial evaluation. To test the system, we adapted an existing Instructable [35] and ported it to the MakeAware system. We did so by separating the tasks into individual steps in the project map. In this case, the map consisted of two branches that could be performed in any order, while tasks within the branches needed to be performed in order. This Instructable helps makers create bookends using a laser cutter and offers a variety of flexibility across fabrication methods and approaches and the ability to use an assortment of tools to complete the task. We brainstormed several fabrication options and tools for each task and included them as options within the project map.

Participants

We recruited twelve novice makers (four female, eight male) from a mailing list of people who had completed the basic safety training in the makerspace we used. They ranged in age from 27 to 57 (mean: 36.3). Our participants were novices and had either "rarely" (7 participants), or "sometimes" (5 participants) used digital fabrication tools. Participants were reimbursed $25 for their time.

Apparatus

Four stations, each equipped with a state beacon, were configured within our organization's makerspace (Figure 2). These stations were based on the equipment required to complete the wood bookends project. The stations included the laser cutter, band saw, workbench with a shelf stocked with hand tools, and a fume hood under which makers could perform painting, staining, and gluing.

Procedure

Participants began the evaluation by filling out a questionnaire which collected demographics and assessed their familiarity with the makerspace we used and the tools and materials involved in the project. They were then given a scripted walk-through of how to use the MakeAware system before beginning the project. Each participant was given 90 minutes to build a set of two wooden laser-cut bookends, which included decorative elements and metal feet. Since we did not intend to evaluate the participants' skills using software tools such as Adobe Illustrator, we supplied a template for laser cutting that participants could modify, but also allowed participants to create their own templates if they wished. At defined steps in the process, we made certain tools unavailable to evaluate how participants would respond to obstacles while using MakeAware. While building the bookends, participants were asked to think aloud; a member of our research team was present to take notes, but the sessions were also audio recorded and video recorded from two angles so participants could be seen while working at any station. At the end of the session, participants filled out a second questionnaire which assessed their experience using MakeAware and how well they thought the features supported their situation awareness and ability to make decisions during the project. Situation awareness questions were worded using generic language so they could be understood by participants who are unfamiliar with the SA framework. Questions pertaining to *perception* used the keyword "notice"; questions pertaining to *comprehension* used the keyword "understand"; questions pertaining to *projection* used the keyword "expectations". We also asked questions to directly evaluate participants' impression of MakeAware's support for decision making by using the keyword "choose".

Data Collection and Analysis

We analyzed the log files collected during our evaluation to determine the number of different paths taken through the project, the number of times each participant used the peeking feature before selecting a task, the number of times they looked ahead in the instructions, and the number of times they interacted with the videos which provided background knowledge they may have been missing. Additionally, we made observations during and after the sessions relating to decision making, situation awareness, and use of the system. We also collected data from our pre- and post-evaluation 5-point Likert scale questionnaires, including self-ratings of previous experience, and ratings of the MakeAware system. We analyzed this data with the intent to determine how well makers were able to plan, adapt and improvise, and keep their overarching goal in mind.

Results

In the next three subsections, we break down how well each level of situation awareness was supported.

Support for Perception (SA1)

MakeAware supported *perception* of environmental cues via tool sensing and showing the locations of the workstations via the coloured bulbs. We hoped this would help makers become aware of how the space around them is being used and which tools and workspaces are currently available.

Our observations revealed that many participants were primarily focused on the task instructions while choosing a task, and only looked to the bulbs for guidance after a task was chosen. As a result, five participants strongly disagreed that their *perception* was well-supported by this feature. However, three participants agreed and one strongly agreed that the state beacons supported their *perception* (Figure 4).

When asked to rate the system as a whole, irrespective of individual features, participants responded that their *perception* was most well-supported compared to *comprehension* and *projection.*

Support for Comprehension (SA2)

We provided features to support *comprehension* in three ways. First, the details provided by the state beacons support comprehension of how the tools in the environment might meet their current needs. Second, the task beacons support the maker's comprehension of how their progress through the project will affect their use of the space. Finally, the project map, including peeking, supports the maker's comprehension of how their current task fits into the project.

Half of the participants agreed (4) or strongly agreed (2) that the environment state details supported their *comprehension*, while half of participants also agreed (1) or strongly agreed

(5) that the project state details supported their *comprehension* (Figure 4). The project map was most successful at supporting *comprehension*. Averaged across two sets of questions, 3.5 responses agreed and 7.5 responses strongly agreed (Figure 4).

Support for Projection (SA3)
Every participant looked ahead at future steps in the project before completing current tasks by looking at the full instructions of future tasks (average 14.8 times per participant across 13 possible instruction pages). All participants except one used the peeking feature to examine tasks at a glance before choosing one (average 7.2 times per participant across 13 possible peeking cards).

The project map supported the makers' *projection* ability, or ability to judge how future states of the project will unfold based on their current actions. One third agreed that the project map succeeded in this way, while one third strongly agreed; the remainder were neutral (Figure 4).

Support for Decision-Making
As per Endsley's framework [8], supporting SA can give novice makers the ability to make better decisions during the course of their project. To this end, makers were explicitly asked in the questionnaire how well the features of MakeAware supported their ability to make decisions during the project. As further evidence of decision-making, we also recorded the number of unique ways makers completed the bookends, and collected quotes and observations related to decision-making during the evaluation.

Responses for how well the state beacons supported decision-making were overall neutral (Figure 5). However, the project map was better received in regards to decision-making. This aligns with our expectations since the project map was intended to support more advanced levels of situation awareness, i.e. *comprehension* and *projection*. Only one participant disagreed that the project map supported them in choosing a method for completing a task. Three quarters of participants either agreed (4) or strongly agreed (5) that the project map supported them in choosing a method for completing a task. All participants either agreed (3) or strongly agreed (9) that the project map supported them in choosing which task to complete next (Figure 5).

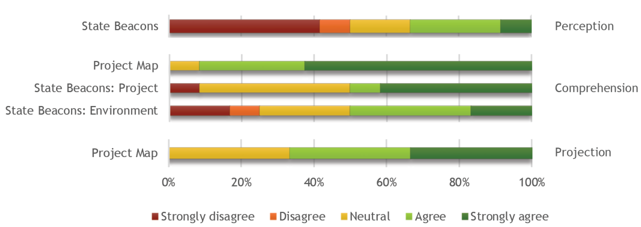

Figure 4: Participant responses for how well each feature supported the level of situation awareness it was designed for: perception, comprehension, and projection.

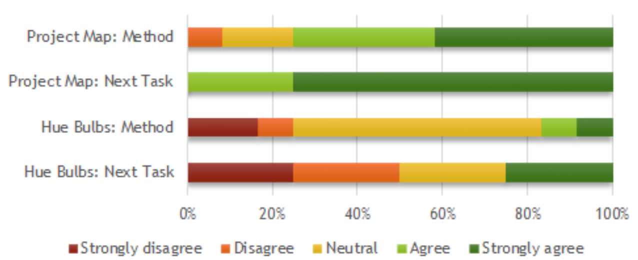

Figure 5: Participant responses for how well the state beacons and the project map supported the makers' ability to make decisions about which task to perform next, and which method they should use to complete the task.

Of the 12 participants, 11 completed the project in six unique ways. One participant did not complete the project by the end of the study and therefore their path was not analyzed. That participant worked too slowly to complete the project in the allotted time but continued working on the bookends on their own time after the session had ended. The six unique completed project paths indicate early success that MakeAware was able to guide people through decision making in a non-prescriptive way, allowing novices to follow a path of their choosing, unlike previous works [e.g. 16]. The six completed paths included four different task orderings and two different methods of completing two of the tasks (Figure 6). This also shows that participants were able to adapt when we introduced obstacles into the process, i.e. unavailable tools.

Participants used various data provided by MakeAware to make decisions about how to proceed in the project, including the videos (e.g. P8), time estimates (e.g. P11), and location of tools (e.g. P5). Many participants provided verbal description of these decision-making processes. For example, while looking through the different options for attaching all the pieces together in the final step of the project, P2 said, *"I'm trying to decide on which way to fasten them best... I think gluing is best."*

Some participants made the decision to try a different approach to a task after attempting another approach. In these cases, MakeAware was able to help them choose a method better suited to their needs. For example, P4 originally wished to use a screwdriver to attach the pieces together, but upon realizing that it would not be easy to do without an electric screwdriver, said, *"Now that I see what's available, I may move to another fastener method."*

These examples show us that these participants actively thought out what they were going to do next before deciding, rather than following a prescribed set of instructions.

DISCUSSION

Meeting Our Design Goals
In the short term, the success of our design goals can be measured by looking for evidence of planning, using knowledge to select the best tool or method, productive responses to obstacles, and maintaining project awareness.

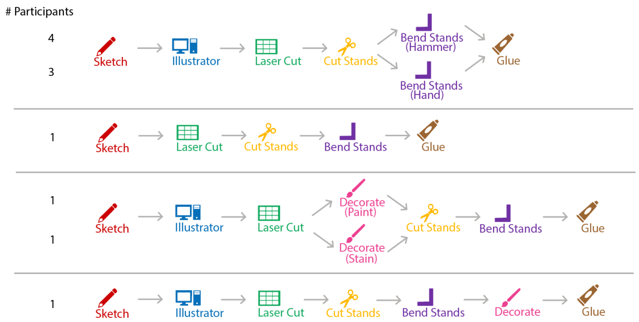

Figure 6: A visual representation of each individual path participants took while completing the project. Six different complete paths were taken by 11 makers.

We saw evidence of planning in the data that shows how all participants looked ahead in the project, either by viewing the full instructions of a future task or by peeking at the task in summary. We also observed that participants used knowledge provided by MakeAware to select tools and methods. This is partially evident from the behaviour of looking ahead and confirmed by quotes from participants about their decision-making process, presented in the previous section under support for decision-making. Based on this, we believe that our design goal 1, which focuses on supporting overall planning, is relevant to the design of systems that scaffold SA.

We made tools unavailable at certain points in the process. Participants were able to adapt when this happened, resulting in six different successful paths through the project to completion (Figure 6). This is evidence that participants had productive responses to obstacles, and that MakeAware as currently implemented was successful in providing non-prescriptive project support that could help novices to improvise (D2). Based on this we suggest that our design goal 2 should be incorporated in future systems for SA.

We did not observe participants getting too carried away by individual steps to achieve the end goal, a novice behaviour commonly described in our expert interviews and in related work, e.g. [16]. It is possible that time constraints associated with the experiment could have encouraged participants to stay on track. However, some of our observations suggest that MakeAware did offer support in this area. Our participants used the project map to look ahead at future tasks; the map also served to explain how each individual step related to the end result of the project. We therefore believe the project map and overview features supported participants in maintaining awareness of both the overarching goal and the current task simultaneously (D3) as intended. More data on which features helped most with this awareness is still required. Based on participants’ success, we suggest that our design goal 3 should be one focus for systems designed to support SA.

Supporting Situation Awareness

The state beacons were rated most useful when they provided project state details, such as when they turned blue to inform the maker about where they will find the tools for their selected task. However, we noticed that the tablet interface, including the project map and instructions, held the makers' attention while they were choosing which task to complete next; this means they were usually too preoccupied to notice the orange colour in the state beacons indicating that certain tools were unavailable. Tool availability was also indicated on the tablet interface using the same colours, e.g. if the tool was unavailable, its listing on the instructions would be highlighted in orange in accordance with the legend of colours appearing on each page. It is not clear at this time whether the reflection of tool availability on the tablet interface was considered useful. It may be worthwhile to investigate how we could better support the *perception* of tool availability using the tablet interface rather than the state beacons to take advantage of where the makers seem to focus their attention. This is also in-line with Endsley’s [8] suggestion that systems display is appropriate for conveying SA-related information.

The environment state details were the main feature we designed with the intent to support *perception*. However, ratings of how well the state beacons supported *comprehension* were higher. This is an interesting finding given that MakeAware as a whole received the highest rating for its support of *perception*. Given how closely each level of situation awareness is intertwined [8], we hypothesize that there may have been some “trickle down” effect from our support of *comprehension* and *projection*, resulting in strong support for *perception* as a side effect.

MakeAware Features

During the evaluations, we noticed a recurring thought voiced by some of the makers about the project map. For the bookends project, the map was laid out in two main branches: one for the wooden structure and one for the metal feet. At the end, both branches met in a final step which outlined how to attach the pieces from both branches together. Five participants initially thought the project map was one long trail of tasks rather than two branches joining together in one end point. This did not stop them from succeeding as they realized upon reaching the final step via one branch that they were missing the pieces from the other. Seven participants understood the map easily and the other five were able to understand it with some exploration. In the future we could add other visual cues to make the map more clear [30].

Although MakeAware was rated more useful than written instructions and instructional videos for completing a project, it was rated less useful than assistance from an expert. This was expected; we intended only for the system to support novices in following a process that exhibited situation awareness, and we observed that our design succeeded in that way.

Limitations

The environment state details in MakeAware work under the assumption that all tools are correctly returned to their respective places when they are not in use. We recognize that this is an idealized assumption, especially in a busy makerspace. However, enforcing this degree of organization in a makerspace could be beneficial to novice makers as it would help them to reliably locate the tools they need.

We designed MakeAware to guide makers through one specific project while working in a particular makerspace. Our current prototype is not setup to automatically generate information for a given project as input. However, in the future, if makerspaces are instrumented with appropriate sensors and documentations such as Instructables collect more structured data about makers' workflows, it would be possible to use our design to create scalable systems.

We manually created the bookends tutorial to adhere to the requirements of MakeAware. One important problem that is outside the scope of the current work is how we can efficiently create tutorials of this type. We can look to other work on non-linear and flexible tutorials for making and fabrication [17, 30] for some inspiration on how we might do this. We created the progress capture feature, where makers record their progress after each task, to support future work in this area. More work is also required to determine how we might create tutorials that also accommodate different makerspaces.

Recovering from mistakes and learning to be resilient is part of the process of becoming an expert maker [28, 29]. We made efforts to reduce the occurrence and severity of errors through MakeAware to prevent novices from being discouraged by failure. We have not tested the effects of this effort on resilience or becoming an expert.

MakeAware is one example of a system designed to support SA. There may be other designs that could support SA for novice makers in other ways using our design goals. It is also worth noting that support for SA does not encompass all aspects of making, such as social interactions.

FUTURE WORK

As next steps, it would be interesting to test how well MakeAware, or other systems supporting situation awareness, helps novices to learn making skills compared to prescriptive instructions. As stated by Kolb [16], active experimentation, drawing one's own conclusions, and reflecting on concrete experiences are important factors in learning. We think that supporting situation awareness will support these aspects of learning more completely than conventional instructional materials, but we have not yet investigated its effect on learning.

Additional considerations we are making going forward include how we can design a makerspace to support situation awareness for more than one maker. The tablet interface could easily be duplicated on multiple devices, but extending the state beacons to support multiple makers is a difficult problem, particularly when they are providing project state information and guiding the maker based on their individual progress. Thus, to support multiple makers we would need individualized state beacons. This may be possible using projected messages rather than coloured lights, which could relay more information; we could also implement a map of the makerspace in the tablet interface that could similarly guide makers and provide environmental cues about other makers using the space.

Observations during the evaluation, supported by questionnaire responses, indicate that a major persisting struggle was not fully understanding how all the bookend pieces needed to fit together once they were all created. This information was contained in the videos but was insufficient. It appears that while situation awareness support helped novices to create all pieces of the bookends, and even to understand the methods of attaching the pieces together (e.g. glue or nails), it did not help to support their understanding of how the pieces should fit together spatially. We believe that more spatial assembly support would be beneficial, and we plan to investigate this problem in future projects.

Other questions we may want to explore in the future include: How might systems like MakeAware make users more resilient to challenges and failure? Do users confidently navigate new projects or environments after using the system, or do they become dependent on it? Would support for situation awareness be useful for expert makers as well?

CONCLUSION

In this paper, we presented design goals to support situation awareness for novices engaged in procedural making and fabrication activities. We also introduced MakeAware, a prototype system based on our design goals. To design MakeAware we drew inspiration from the making processes of expert makers uncovered in our interviews, and the struggles of novice makers presented in related work. Our current prototype system was evaluated by 12 novice makers who used it to build a set of laser cut bookends.

From observations during the evaluation sessions and questionnaires about the system, we found that the project map feature was very helpful in supporting *comprehension* (SA2) and *projection* (SA3). Metadata provided in the tablet interface such as videos, task instructions, and images of the outcome were also found to be helpful for developing background knowledge, which in turn helps with developing SA2 and SA3. The environment state details designed to support *perception* (SA1) were found to be moderately useful and participants understood that it helped to guide them spatially.

Ultimately, we found that designing around situation awareness helped novice makers to put more emphasis on planning ahead (D1), to make decisions during the course of the project (D2), in a way similar to experts.

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