Merging Sketches for Creative Design Exploration: An Evaluation of Physical and Cognitive Operations

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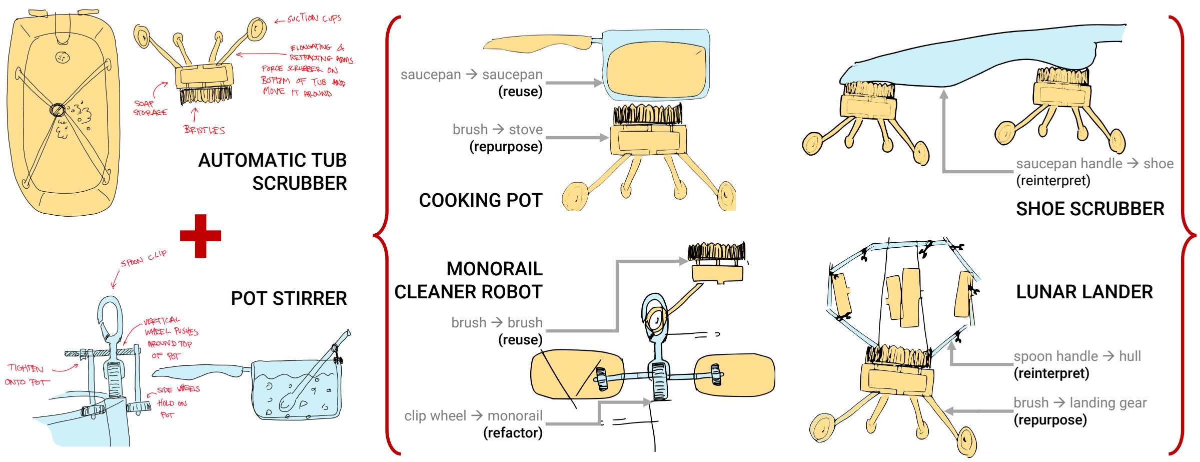

Figure 1: A sample of sketches merged by participants of our study. The two sketches to the left were the inputs to the participants, and the four sketches within the curly braces were created by merging components of these two source sketches. The source and merge sketches are colored post-hoc to indicate the components that were used in the merge. The sketches are labelled by coders to indicate the kinds of cognitive operations (defined in this paper) used in each of the merged sketches.

Abstract

Despite its grounding in creativity techniques, merging multiple source sketches to create new ideas has received scant attention in design literature. In this paper, we identify the physical operations that in merging sketch components. We also introduce cognitive operations of reuse, repurpose, refactor, and reinterpret, and explore their relevance to creative design. To examine the relationship of cognitive operations, physical techniques, and creative sketch outcomes, we conducted a qualitative user study where student designers merged existing sketches to generate either an alternative design, or an unrelated new design. We compared two digital selection techniques: freeform selection, and a stroke-cluster-based "object select" technique. The resulting merge sketches were subjected to crowdsourced evaluation of these sketches, and manual coding for the use of cognitive operations. Our findings establish a firm connection between the proposed cognitive operations and the context and outcome of creative tasks. Key findings indicate that *reinterpret* cognitive operations correlate strongly with creativity in merged sketches, while *reuse* operations correlate negatively with creativity. Furthermore, *freeform* selection techniques are preferred significantly by designers. We discuss the empirical contributions of understanding the use of cognitive operations during design exploration, and the practical implications for designing interfaces in digital tools that facilitate creativity in merging sketches.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Interaction Styles; I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques

1 Introduction

The act of designing is often characterized as a combination of divergent and convergent thinking [26]. Divergent or creative thinking involves the generation of several ideas that address the design problem at hand, while convergent or analytical thinking involves the evaluation of these ideas to choose the best candidates. A sound design practice invovles multiple iterations of divergent and convergent processes until a satisfactory solution is found. Designers often draw from existing sources of inspiration when generating ideas or synthesizing variations. Several techniques have been proposed for aiding divergent thinking by drawing inspiration from one's surroundings and making connections between them [19], or combining or modifying parts of existing ideas [22]. Such techniques help reframe the design problem and use existing designs to generate new ones.

The concept of borrowing and adapting existing content to create one's own—what is often called the "remix culture" [18]—has

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existed for some time, and has particular relevance in digital contexts. This notion has also been supported in CAD systems through parametric design practices [7], in programming through software versioning systems, and more recently, in Maker cultures through online communities [24]. Computational support for combining and modifying content has been limited to content that has a clearly defined syntax (e.g. programming, 2D drafting), or form (e.g. images, 3D models). However, the design sketch, often seen as an intentionally ambiguous representation of an idea, does not lend itself readily to combination or modification.

Our goal in this paper is to explore the process of creating new ideas by combining components of existing sketches of ideas. We study the physical act of *merging* sketches of existing ideas, as well as the cognitive aspects of changing the function and/or context of these components to create new ideas. In a traditional paper-based design scenario, the merge operation may be performed by redrawing a new sketch that incorporates themes from source sketches, or by physically cutting and pasting together the new sketch from its source materials. The latter approach is adapted to digital scenarios using digital 'cut', 'copy', and 'paste' operations. Digital settings thus do not require completely redrawing or physically destroying the source materials, and are thus significantly more time- and resource-efficient. Digital media also support the transformation of sketch components through translation, rotation, and scaling.

Furthermore, few digital design tools provide support for merging design elements from the source sketches to create entirely new ideas and concepts. The support for efficient merging of sketch components is more critical in collaborative design, where quick access of visualized ideas from multiple sources is important. In this paper, we remedy this gap by examining the physical and cognitive aspects of selecting and merging parts of existing sketches. In the same way that sketching, a physically expressed process, acts as an extension for the designer's memory, reducing their cognitive load, we propose cognitive operations involved in merging sketches, namely *reuse*, *refactor*, *repurpose*, and *reinterpret*, based on the preservation or change of context and function.

We identified connections between the physical and cognitive aspects of merging through a three-stage study. First, we conduct an in-depth qualitative user study involving 19 designers combining sequences of two pre-drawn source sketches into a single output sketch. The study involved the divergent process in two forms. The first was a context-preserving *functional* merge, where participants were asked to combine the source sketches into an output sketch that incorporated ideas from both. A context-changing *exploratory* merge task required them to use elements from both source sketches to create an output sketch with entirely new ideas. We compared the qualitative performance for this merge operation in both phases for paper as well as digital settings. We tested two digital selection techniques: free-form selection where users could "cut" and use parts of a sketch as they do with paper, and an object-selection technique that used sketch clustering [39] to support the selection of composite sketch elements. To better elicit the effect of these differences from participants, we also asked them to perform one merge task with paper using traditional cut/paste methods. Second, we conducted crowdsourced evaluations to determine the originality, and in the case of the context-changing tasks, the dissimilarity of the merged sketches. In the third stage, we coded the merged sketches to identify the cognitive operations used in each merge task.

We identified a significant correlation between originality and the use of *reinterpret* operations (changing both context and function) in merged sketches from *exploratory merge* tasks. However, negative correlations were found between the use of *reuse* operations (preserving both context and function) and the originality and dissimilarity scores. We also found that participants used *reuse* significantly more during functional merges, and *repurpose* during exploratory merges. Finally, participants who used the object select method had significantly higher instances of *repurpose* operations. Our findings establish a firm connection between our proposed cognitive operations and the context and outcome of creative tasks. Finally, while the selection technique based on sketch clustering was not preferred by the participants, their comments suggest that exploration of this technique with different clustering metrics holds promise for aiding creative design exploration.

2 BACKGROUND

Resolving and combining ideas, concepts, and content from multiple designers is a canonical operation in any collaborative process involving the creation of new artifacts [28]. In this paper, we limit our scope to creative design, where the goal is to generate and develop ideas—for any area concerning the constructed world, including products, visuals, and interfaces—and where the *sketch* is the primary medium of communication. In its basic form, a sketch is a rapidly created freehand drawing intended for visually exploring ideas [20, 34]. In this section, we review the literature on sketching and perception, collaboration for design, and collaborative editing.

2.1 Inspiration vs. Fixation

Design is often seen as a search for solutions to a problem by drawing analogies or inspiration from one's surroundings [10]. Designers often create new ideas by combining existing ones [2]. However, inspiration is a double-edged-sword: pictorial sources of inspiration often limit the designer's thinking to the extent that they are unable to think beyond a given example to reach a solution. This barrier, termed "design fixation" [14], is a major barrier to creative output, inhibiting the exploration of the design space [14]. There exist several techniques to delay fixation and support creativity, such as SCAMPER [22], a mnemonic of a set of techniques to abstract or change ideas, or the abstraction of solutions to a general domain before re-applying them [37], or collaboratively developing other's ideas rather than ones own [32, 35].

At the digital end, computational models have been proposed to abstract design patterns from one domain and analogically transfer them to another [9]. Another approach is the utilization of shape grammars to suggest new or alternate abstract configurations to the designer [23]. However, surpassing the domain-specific knowledge and analogical thinking of the human designer is yet to be achieved. Computational tools should enable the designer in the reinterpretation of structures and functions, allowing them to transform existing ideas into new ones through the combination, modification, and extension of existing ideas.

2.2 Visual Perceptions in Sketching

Sketches play an important role in externalizing ideas during early design by providing a visual database of generated ideas that inspires new ones [20]. In fact, sketches in particular have been shown to be more effective than any other medium, including text and cross-representational techniques, for the early phases of ideation and creativity [21]. Sketches serve to inform the design process, both for building on existing ideas as well as exploring new parts of the solution space. The act of sketching is simultaneously a physical and mental process, with the sketch not only serving as an extension of the designer's mind, but also a medium with which to communicate, regroup, and reinterpret ideas [34]. Designers have also been known to make unexpected discoveries in the act of sketching when they interpret their own sketches in ways they had not originally intended [17].

The idea of multiple perceptions of the same sketch is important to creative support. Prats et al. [25] categorize the different levels of shape transformations that occur when designers sketch, into general rules with which to interpret the changes to a sketch. Just as the act of sketching helps the designer think, the ability to manipulate sketches, or parts of sketches can help the designer discover new

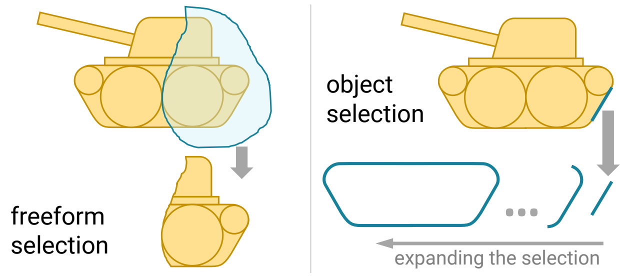

Figure 2: The two selection types considered for this study. Freeform or area-based selection is seen in image editors and other graphical applications. The object selection type is a stroke-based selection that extends the initial selection of one stroke to include other temporally clustered strokes. Figure 3 details the clustering mechanism.

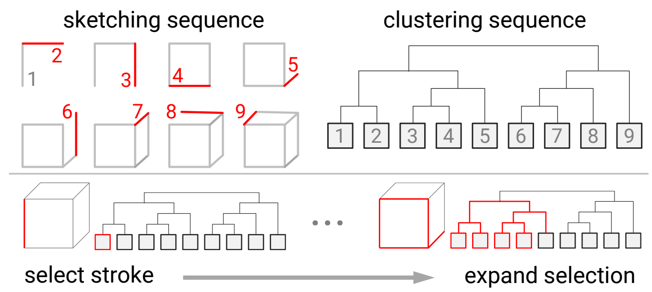

Figure 3: An illustration of the sketch history-based clustering technique for grouping strokes into objects, and the expansion of selection by traversing to the parent nodes of a stroke (cluster) in the tree layout.

ideas. Supporting visual regrouping of ideas using digital sketch editors that incorporate Gestalt-like rules has been proposed earlier [30,31]. Using the sketching process itself to organize and group strokes to cohesive units has also been proposed [39]. In this paper, we will explore the selection and reorganization of sketch strokes using conventional freeform and stroke-clustering based techniques on a pen-and-touch interface to aid the designer in selecting and transforming existing sketches to form new ideas.

2.3 Digital Support for Creativity

Pen and paper has long been the gold standard for sketching [3, 34], but the emergence of high-quality pen-input devices is starting to make the digital medium more attractive in a wide range of domains, including automotive design [16], architecture [5], and software design [4]. Several studies have explored how to replicate the strengths of paper—familiarity, precision, and accessibility—even on digital devices [1,36] in order to harness the strengths of the digital medium, such as persistence, replication, and composition. When suggesting design guidelines for creating creativity support tools for sketching and composition, the focus has been on supporting exploration [27], especially the ability to move forward with an idea, backtrack, try alternatives, and support the inclusion of multiple people and tools.

Given the prominence of sketches as a natural communication medium for collaborative design, many digital creativity platforms are centered on these artifacts. TEAM STORM [13] is a groupware system for co-located sketching, where designers have both private and group workspaces and mechanisms for exchanging artifacts between them. IdeaVis [8] combines the strengths of both paper and digital media using a hybrid workflow that incorporates both high-resolution displays and Anoto pens for collaborative sketching. GAMBIT [29] is a web-based system for sketching user interfaces in co-located collaboration involving multiple devices and displays. Finally, skWiki [38] is a collaborative sketching platform that enables collaborators to branch from any sketch.

While digital creativity platforms offer means to generate different alternatives to existing sketches, there needs to be a better understanding of the various physical and cognitive processes that are involved in merging sketches, instead of borrowing processes from similar operations in coding and document editing. The goal of this paper is to understand these processes and how they, through digital sketching and merging tools, can support design exploration.

3 Design Framework: Merging Sketches

We call the operation to combine two[1] source sketches A and B into a new resulting sketch C a *merge* (or "sketch merge"). To understand what happens in the sketch merge operation, we need to separate the physical aspects of the process from its cognitive aspects. By physical aspects, we mean the parts of the operation that are expressed externally by the designer: operations such as select, cut/copy, paste, rearrange, and compose. By cognitive aspects, we mean the parts of the operations that occur internally, in the designer's mind. This involves the designer's internal representation of what the sketches denote: the ideas expressed in the source sketches, or newer ideas that are formed in the designer's mind when parts of these source sketches are isolated or combined. These two aspects of merging are intricately connected: sketches are external representations of the designer's evolving thought process [12], and identifying these aspects may help understand how they come together.

3.1 Physical Operations in Merging

The physical operations that come into play when merging sketches can be categorized into two kinds of processes:

- **Selection:** This is the process by which a part or parts of source sketches are selected.
- **Transformation:** Translating, rotating, and scaling the selected parts to form the merged sketch.

3.1.1 Selection

At a physical level, selection involves identifying and demarcating areas of interest from the source sketches. We identify two forms of selection in the context of sketching:

- **Freeform selection:** Commonly known as "lasso select" in existing drawing and photo manipulation editors, this requires the marking of a freeform shape depicting the area of interest, and selecting everything that lies in this area.
- **Object selection:** While freeform selection is a natural choice for most image-based media, sketches are also collections of strokes, and it makes sense to have a selection mechanism that is aware of this. This idea is not new: drafting applications allow the selection and manipulation of lines or groups of lines, either directly, or by chaining connected lines/curves. This allows selecting coherent "objects" inferred in the sketch.

These two forms are shown in Figure 2. Note that sketches consist of unorganized strokes and not discrete objects. Contrast this with traditional vector editors, where illustrations are created using geometric shapes and paths. To implement object selection, we addressed the issue of stroke organization by using an agglomerative stroke clustering method based on the time and order in which the strokes were created [39]. The strokes in a sketch are thus combined into clusters based on a proximity measure and temporal order, and these clusters (a group of strokes) are further combined with other strokes or clusters using the same approach. This recursively

[1]We limit our treatment here to two source sketches, but these ideas should generalize to a higher number of source sketches.

builds a tree-like structure (a dendrogram) representing the clustered sketch (stroke) histories (as illustrated in Figure 3. Note that the root cluster on this tree represents the entire sketch, while the leaves represent individual strokes. Selecting a particular stroke allows us to expand the selection using the cluster hierarchy (by moving to the closest parent in the tree); by giving users control over this, they can smoothly expand or shrink their selection.

This is just one automated clustering algorithm that can used for this purpose; there are many other alternatives from the data analytics domain including k-means and k-d trees. Our approach uses agglomerative clustering as it creates a hierarchy of stroke clusters, which is amenable to the process of "expanding" a stroke selection. Overall, selecting a specific sketch part that conceptually belongs together—such as a wheel on a car, a person in a room, or a part in a schematic—becomes significantly more efficient than freeform selection.

3.1.2 Transformation

Once the designer has selected a visual element to transfer from one of the source sketches to the resulting sketch, they may want to transform the element in the final result. Examples include changing the location, size, or orientation of a selected element in the composition. To accommodate this, the merge operation incorporates translation, freeform scaling (with non-fixed aspect ratios), and rotation for each individual element.

3.2 Cognitive Operations in Merging

In conceptual design, shapes represented in sketches are ambiguous, leading to multiple interpretations that support design exploration [15]. Such exploration can be used to delay fixation by abstracting a concept and re-representing it in a different domain [37], or by the use of techniques such as SCAMPER [22] to change certain components, functions, or the domain of an existing concept. These methods form the basis of the cognitive operations that we introduce in this paper, that we categorize along two dimensions: *function* and *context*. Function is the role a component plays in the original or source sketch, whereas context is the domain in which the component or its parent sketch exists. When a designer performs a merge, components that go into the merged sketch can either have the same or different function, and can exist in the same or different context, as in the source sketch. Just as sketching is a physical expression of the designer's thought process, we posit that the physical acts of selection and transformation express the designer's cognitive processes of abstraction and re-representation. We identify four cognitive operations that can occur when a sketch C is created by merging elements from sketches A and B.

Reuse: The use of a component from A or B in C where both the function and the context of this component in C is the same as in the source sketch. *Reuse* is often seen when generating alternatives for a design problem by choosing parts of existing design solutions. This is illustrated in Figure 4 as the use of the tank tread on the undercarriage of the helicopter. The tread performs the same function as it did for the tank. This can be seen as a representation of Goel's lateral transformation [11], where a sketch undergoes a modification to one that is similar to, yet distinct from, its earlier version.

Refactor: In computer science, *refactoring* is the process of reorganizing a program's internal structure without altering its external behavior. We interpret the term here as the use of a component from A or B such that it performs the *same function* in C as it did in the source, but in a *different context*. This is illustrated in Figure 4 by the use of the tank's armored body as the fuselage of the helicopter. It performs a similar function as it did earlier (protect and house the occupants), but in this case, it is now in the context of aviation. Refactoring can help in design space exploration by abstracting the function represented by a part of the sketch.

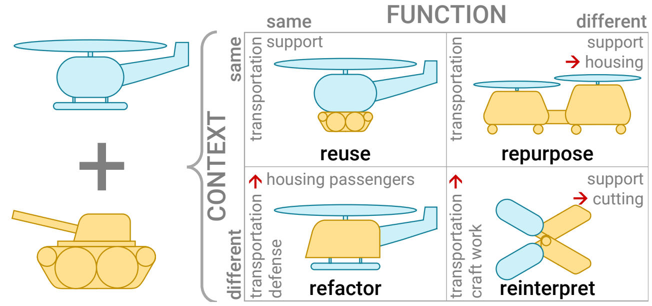

Figure 4: The cognitive operations identified when merging two sketches to create a new idea. "Reuse" operations use the merged components in the same context and function as in the source sketches. "Reinterpret" operations change both the context and functions of merged components are changed, and the merged idea is very different from the sources. "Repurpose" and "Refactor" occupy the remaining positions in the function-context matrix.

Repurpose: Here a component from sketches A or B is used in C in a way that it occupies the *same context* or domain as the original sketch, but performs a *different function*. This operation often uses the form of a component of a sketch to replace a different component. For example, in Figure 4, the outline of the tank tread is repurposed to now play the role of the fuselage of the helicopter.

Reinterpret: Finally, reinterpretation is when an element from A or B is used in the merged sketch C such that it performs a *different function* in a *different context* from the source sketches. This operation could be particularly useful in design space exploration as it creates results that are the most different from the source sketches. In the example shown in Figure 4, components of the tank and the helicopter are completely reinterpreted to create a pair of scissors. Our definition of reinterpretation is derived from Suwa et al.'s [33] perceptual reorganization, where regrouping parts of sketches provides new interpretations.

3.3 Paper vs. Digital Media

In traditional design settings conducted using paper, merging two source sketches often happens in many different ways. For instance, the designer can combine ideas from source sketches by simply drawing a new sketch from scratch. Other options include tracing over parts of the source sketches, or cutting out copies of the source sketches to create a collage-like merged sketch. Note that when sketching on paper, transforming the selected parts of the sketch is not trivial. Paper allows for only rotation and translation, but for scale, it would need additional mechanisms such as pantographs (for tracing a larger shape), or photocopiers (for creating a larger sketch to cut out). The *recreate from scratch* option does allow for all transformations, but is dependent on sketching skill.

Digital sketching platforms have both strengths and weaknesses compared to traditional paper-based sketching [1, 38]; one of the oft-cited strengths is the possibility to effortlessly reproduce a sketch without consuming the original. We performed a study of such merging operations under two different design situations, in order to understand the physical and cognitive operations involved, and the role of the medium in supporting these operations.

4 Study Methods

In the previous section, we outlined the physical and cognitive operations of merging sketches, with possible implications on the outcome. To understand how these operations affect the results, we conducted our study in three stages:

1. **User Study:** We examined how designers merged two sketches using a merging interface we created specifically for this study.

The goal was to understand how designers use merging techniques under different design scenarios.

2. **Evaluation of Sketches:** We performed a crowdsourced survey where respondents were shown a set of sketches created from the same pair of source sketches by participants from (1). They were asked to choose sketches that were (a) the most different from the sources, and (b) represented the most original idea.
3. **Coding of Cognitive Operations:** We coded each merged sketch to identify the number of unique occurrences of each of the four cognitive operations.

4.1 User Study

The focus of this study was to understand divergent thinking under two conditions: (1) a "functional" merge, where the source sketches are possible solutions to the same design problem, and (2) an "exploratory" merge, where the source sketches are unrelated to each other. In the case of the functional merge, the design task was to generate a merged sketch that addresses the *same design problem* as the source sketches, while in the case of the exploratory merge, the design task was to generate a merged sketch that is *completely different* from the source sketches. These tasks represent the extremes of design exploration: the functional merge focused the exploration of alternatives to a specific domain, and exploratory merge removes all constraints. They also serve as a check for our cognitive operations: functional merge should require more reuse operations, while exploratory merge, more reinterpret operations.

4.1.1 Participants & Materials

We recruited 19 paid participants (4 female, 15 male), 16 of whom were students of a senior course on toy design, while three were graduate mechanical engineering design majors. With an age range of 21 to 28 years, all had novice to intermediate level skill in sketching on paper. Seventeen were right-handed, and 13 were comfortable using tablets and styli. All demographics were self-reported.

The digital parts of the experiment used a Samsung Galaxy Note 10.1 2014 edition tablet using the S-Pen™ with a < 1 mm tip. For paper, we opted for the "cut and paste" among the options discussed in Section 3.3, because it was practically feasible within the time limits of the study. Source sketches were printed on different-colored letter-size papers (8.5×11 in.), and participants were provided with scissors, glue, and a blank sheet of white letter paper for the merged sketch. The goal was to give participants a reference point of merging practices, using the most common medium to assist them when reflecting on the digital techniques.

4.1.2 Tasks

In the digital medium, participants used two selection techniques (freeform and object) while performing two merge tasks (functional and exploratory). We developed an Android application for each of these techniques. The visual space on the Android device display was divided into two main areas corresponding to the physical operations discussed earlier: a *selection view* where two source sketches were displayed from which the participants could select elements, and a *transformation view* where they could apply transformation operations to the selected elements. Participants were free to orient the tablet or paper to their comfort. Each merge operation outcome was stored on the tablet before the participant moved on to the next task. At the end of each task, the participants' brief description of their creation was recorded. The participants also conducted one merge task (assigned randomly) on paper with the given materials.

In both the functional merge and exploratory merge tasks, participants performed tasks using two different merge techniques on the tablet: freeform selection and object selection. All transformations discussed earlier were enabled, with standard tools for scaling, translating, and rotating the selections.

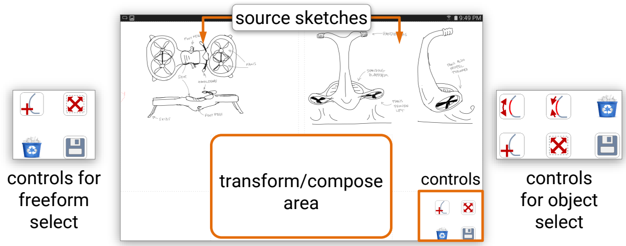

Figure 5: The interfaces of the applications used for the freeform and object select methods. The two source sketches are placed in juxtaposition to the "merge area", where the selected sketch segments can be placed, transformed, and composed for the merged sketch.

We used eight pairs of annotated sketches, created by two expert designers, as the source sketches for these tasks. Four pairs were used for the functional merge task, where each pair presented two solutions to the same design problem. The remaining four pairs, used in the exploratory merge task, presented sketches that addressed different design problems. The source sketches were processed to have similar visual appearance in terms of the stroke width, colors used, and perspective of view to minimize the effects of sketch quality on the merge outcome.

4.1.3 Experimental Design

We manipulated two factors in the experiment: **Situation** (*S*) represented the design task (functional or exploratory merge), and **Technique** (*T*) represented the selection method used (freeform or object selection). We used a full-factorial within-subjects design, with 2 situations (S), 2 techniques (T), and 2 repetitions with different source sketches, for 19 participants, yielding 152 total trials (8 per participant, training excluded). This does not include the paper task, which had only one trial. We counterbalanced the order of both situation S and technique T to minimize learning effects.

We chose to not analyze medium (digital vs. paper) as a factor because our aim was to identify and compare merge techniques used in the digital medium. However, using a paper-based task expands our understanding of the benefits of the digital merge techniques compared to the paper-based merge, which is familiar to participants.

4.1.4 Procedure

The participants were introduced to the purpose of the study and the data to be recorded. They completed a pre-survey on their demographic data, design background, and their experience with sketching on tablets. We then provided instructions for the first stage of tasks (functional or exploratory merge) and gave them time to practice the assigned selection technique and the transformation operations. Training time ranged from 3 to 5 minutes per technique.

This was followed by a set of four merge tasks (for situation S) with two merge techniques (T). Participants were given 5 minutes to complete each task. We determined this time limit through a discussion with the expert designers who created the original sketches; the purpose was to pick a short duration amenable to quick ideation.

Prior to each task, the source sketches were briefly explained. The participants were asked to infer more detail from the annotations and ask questions if necessary. At the end of each task, the participants were asked to explain the idea represented by the merged outcome. After using each technique T, they also completed a survey about their experience with the merge technique they used. A five-point Likert scale was used to understand aspects such as ease and success in selection/transformation, while open-ended questions explored preferences of selection and transformation techniques. Participants then repeated the process for the next situation S.

Finally, the paper-based merge task was explained to the participants, after which they were given five minutes to create the merged paper sketch by cutting and pasting parts of the source sketches. The administrator was present throughout the session to monitor the tasks and provide any clarifications if needed. The sessions were also video recorded. A typical study session lasted 70 minutes.

4.2 Crowdsourced Evaluation of Sketches

Keeping in mind our original goal of understanding the effect of the selection technique on the final outcome of the merge, we evaluated the participant-generated ideas on their originality. Additionally, to determine the extent of how different the outcomes from the exploratory merge tasks were from the source sketches, we also decided to evaluate the merged sketches on their dissimilarity from the source. We therefore collected the merged sketches and performed a crowdsourced online survey (voluntary) via university mailing lists.

A total of 167 sketches were obtained (4 lost trials), where each of the 8 sets contained on average 21 merged sketches. Respondents to the crowdsourced survey were asked eight questions concerned the *originality* of the sketches merged from all 8 pairs of source sketches. Four more questions concerned the *dissimilarity from source sketches* of the outcomes from the exploratory merge tasks.

Each question had the same format: the two source sketches were shown along with their descriptions, and 4 options were presented, along with descriptions of each merged sketch. For each respondent, these 4 options were generated randomly from the pool of 21 merged sketches (from each pair of source sketches). The respondent was asked to select from the options, the most original idea (for the first 8 questions), or the one most dissimilar from the sources (for the remaining 4 questions). We showed only 4 choices, instead of all 21, to make it easier for the respondent to choose. With enough participants, the randomization would ensure that each merged sketch received sufficient representation. The options shown to each respondent and their choice were both recorded.

Respondents were also required to briefly explain the rationale for their choice for each question in a text field provided. This served as a means for eliminating spurious responses: if a rationale was not provided, that response was removed from our evaluation. A total of 175 initial respondents were thus pruned down to 120 people (60% female, 39% male, 1% unidentified), chiefly university students and faculty (49% engineering, 19% information sciences, 8% education, and 23% from other fields). Not all participants answered all questions. The valid responses ranged from 88 for the most-answered question to 40 for the least-answered question. On average, we received 53 responses per question. Since each question was independent of the others, we could still consider each of the valid responses. We calculated the following score for each sketch:

$$M_{score} = \frac{(\#sel) - (\#nsel)}{(\#sel) + (\#nsel)} \quad (1)$$

Here #*sel* is the number of times a particular sketch is selected by the crowd, while #*nsel* is the number of times a particular sketch is shown as an option, but not selected. This normalizes the score for each sketch based on the number of times it appears as a choice.

4.3 Coding Cognitive Operations

As discussed in Section 3.2, we identified four cognitive operations that are possible when a component from a source sketch is incorporated into the merged sketch: *reuse, refactor, repurpose, and reinterpret*. We analyzed each merged sketch, and used the corresponding participant descriptions to interpret the role of each component used from the source sketches. Once the role was identified, we coded this element as an instance of one of the above four cognitive operations. Each merged sketch could thus have at least one instance of these four operations. We did this only for unique roles: e.g., if a component was *reused* as a wheel 3 times, it counted as only one instance of *reuse*. We recorded the number and kind of each cognitive operation used in each merged sketch. A sample of the coded sketches is shown in Figure 1. This coding was conducted by three of the investigators of the experiment after anonymizing the sketches, and obfuscating the crowdsourced results from the sketches. Their inter-rater reliability was calculated to be 0.82 (Cronbach's alpha test). A total of 560 operations (32.1% reuse, 31.1% refactor, 4.5% repurpose, 32.3% reinterpret) were identified for 167 merged sketches.

5 Results

We first computed the difference in participants' experience with the selection techniques. To assess the impact of selection techniques and cognitive operations on the outcome, we calculated correlations, (1) between the crowdsourced originality/dissimilarity sketch scores and the selection methods (lasso/object), and (2) between the crowdsourced scores and the number of cognitive operations in each merged sketch.

5.1 Feedback on Selection Techniques

Participants' feedback on the selection techniques did not follow a normal distribution. We thus conducted a non-parametric Wilcoxon signed rank test, which showed that for the functional merge tasks, participants rated the freeform select technique as significantly easier ($Z = 3.69$, $p < .001$) and more successful ($Z = 2.95$, $p = .002$) than the object select technique. The test also showed that for the exploratory merge tasks, participants considered the freeform select technique significantly easier to use than the object select technique ($Z = 3.01$, $p = .002$). However, participants did not rate the freeform select technique as significantly more successful than the object select technique ($Z = 1.33$, $p = .19$). A comparison with paper was not performed as each participant used paper only once, and for only one of the two merge tasks.

5.2 Correlations between Operations and Outcomes

We detail below the kinds of correlations calculated and obtained between the merge situations (functional/exploratory), merge techniques (freeform/object), cognitive operations (reuse, refactor, repurpose, reinterpret), and the crowdsourced study scores for originality and dissimilarity calculated using Eq. 1.

Originality & Cognitive Operations: For sketches generated with functional merge, no significant correlation was found between the originality scores and the cognitive operations. For the exploratory merge tasks, there was a significant negative correlation between originality and the number of reuse operations (Pearson's $r = -0.23$, $p = .033$), and a significant positive correlation between the originality score and the number of reinterpret operations ($r = 0.28$, $p = .011$).

Dissimilarity & Cognitive Operations: There was a significant negative correlation between dissimilarity scores of exploratory merge sketches and the number of reuse operations ($r = -0.53$, $p < .001$), and a significant positive correlation with the number of reinterpret operations ($r = 0.41$, $p < .001$).

Merge Situation (S) & Cognitive Operations: To examine the relationship between the four cognitive operations and the two merge task conditions, we conducted a multivariate test. The results showed that participants used significantly greater number of reuse operations ($F(1,157) = 4.28$, $p = .04$, partial $\eta^2 = 0.03$) and repurpose operations ($F(1,157) = 13.71$, $p < .001$, partial $\eta^2 = 0.08$) in functional merge tasks than in exploratory merge tasks. The participants used significantly more reinterpret operations for exploratory tasks than function tasks ($F(1,157) = 46.69$, $p < .001$, partial $\eta^2 = 0.23$).

Selection Technique (T) & Cognitive Operations: To examine the relationship between the four cognitive operations and the two selection techniques (freeform & object), we ran correlation tests that showed significant correlation between selection methods (freeform select, object select) and the repurpose operation (Kendall $\tau = -0.17, p = 0.02$). This suggests that participants who used the cluster method are more likely to use repurpose. There were no significant correlations between selection methods and the three other cognitive operations.

6 Discussion

We discuss here the findings regarding cognitive and physical operations used during sketch merging, and their implications.

6.1 Cognitive Operations during Merge

We posited that reuse represented an exploration of design alternatives rather than of original ideas. This was confirmed by the negative correlation between the number of reuse operations during sketch merging, and the originality and dissimilarity ratings. However, this correlation was only observed for exploratory merge tasks, and not during functional merge. This may be due to the nature of the functional merge task: participants were constrained to stay in the same context, i.e. to address the same problem as the source sketches. The significantly higher numbers of reuse and repurpose operations in functional merge tasks support this argument.

We also posited that the reinterpret operation represented a reorganization of the designer's perception of the existing sketch [33]. This was confirmed by the positive correlation between the dissimilarity and originality scores and the number of reinterpret operations, and by the significantly higher number of reinterpret operations in the exploratory design task. While significant correlations were not observed between the merge tasks and the refactor and repurpose operations, a more nuanced selection of merge tasks designed to elicit more varied instances of 'lateral transformations' [11] would further explain the relevance of these tasks to design ideation.

6.2 Selection Techniques

Participants clearly preferred the freeform select techniques over object select and paper-based techniques. One reason is because the freeform selection technique is standard in most graphical editing tools, and thus familiar to participants. However, 15 participants reported that there were portions of the sketches they were *unable to avoid* with freeform selection when they were trying to select something else. One participant observed, "*It was sometimes difficult to exclude internal shapes; strange lasso patterns were necessary to avoid them*." This is because freeform select interprets the sketch as an image, not as a collection of strokes representing ideas expressed over time. In most graphical editors, this issue is side-stepped by using layers or selection filters.

The number of tasks on paper was not enough for a statistical comparison, though doing this task at the end provided participants perspective to reflect on the digital techniques. Participants liked the paper-based selection technique more than object select, but were less impressed with the irreversibility of this medium, stating "*I did destroy some parts getting to the pieces I wanted*", "*I really wish I could duplicate some of the parts like in the tablet version*", and "*no undo*" as issues.

The object-based selection technique was the least preferred, and participants cited issues with control and predictability using this technique. Twelve participants found it difficult to select specific parts of the sketches, and one participant reported: "*I had no way of knowing what would be selected next, so I spent most of the time blindly adding and selecting new starting points to avoid what I did not want*." However, some participants found it useful, stating, "*Sometimes the object select mode has better results. I can select the contour of a sketch and avoid the things inside for once.*"

Our intent with the object select technique was to explore an alternative that would suit sketching applications by grouping strokes into objects that could be interpreted, abstracted, and changed. While this technique could potentially provide access to semantic structures in the sketch, the problems seemed to stem from the distance metric for stroke clustering. This metric made it sensitive to the context in which the sketch was created, but was not flexible enough to accommodate the participants' mental "chunking" of the strokes. On the other hand, unpredictability sometimes led to serendipitous discoveries, as a participant observed, "*although sometime* [sic] *the selection wasn't your original idea, it may inspire you with other ideas that would also work*." Further analysis with different clustering techniques is needed to determine which approaches can flexibly support the way designers mentally chunk parts of sketches.

6.3 Design Implications

Existing tools for modification and merging, as stated earlier, typically do not differentiate between sketches and images. Drafting technical drawing tools do a better job of approaching drawings as collections of strokes and symbols, but are aided by the rigid syntactic elements of such drawings. The "thinking sketch" created by the designer as a nonverbal accompaniment to their thought process is very different from the "prescriptive sketch" of the draftsman [6]. We sought to understand how parts of the thinking sketch can be abstracted and re-represented to support design exploration.

The object-based selection technique, though unpopular, opens up possibilities for grouping strokes that might be amenable to abstraction. It is likely that a designer, when creating a thinking sketch, sketches the rough idea first, and fills in details later. Appropriate clustering metrics based on spatial *and* temporal proximity may help separate the rough idea from the detail, something that may not be possible through lasso selection or even manual grouping. On the other hand, for reusing an idea in the same, or a related context, simple lasso selection may suffice. There is thus a need for more flexible means to cluster strokes, using different distance metrics, allow the user to intervene and guide the clustering process, and adapt to different design scenarios. This can begin with incorporating the ability to switch between object and freeform selection, or incorporate a hybrid: use freeform selection to define an area of interest, and use object selection to abstract out the ideas in this area. Further work is needed on more open-ended studies using combinations of distance metrics for clustering could hold the key to an appropriate mechanism for selection and composition.

7 Limitations and Future Work

This study is not intended to be an exhaustive exploration of the design space of sketch-merging in creative design. We restricted the scope of our work to stroke-based sketches as the only form of design output. While the literature suggests such sketches as the primary communication medium in collaborative design [21], there are other media such as text, annotations, and scrapbooks where our work cannot be applied. Additionally, the close interaction between physical and cognitive operations complicates the understanding of the merge process. However, we contribute empirically by revealing the affordances of different physical operations and patterns of cognitive operations in different scenarios of sketch merging.

Our interaction design was guided by discussions with our professional design collaborators, and is not an attempt to reach an optimal layout, visual representation, and workflow. As we mention in our discussion on selection operations, the object-select technique has the potential to better tune selection operations to how designers "chunk" sketches. Future research is need to explore a more exhaustive study of clustering techniques to achieve a grouping that mimics this chunking. For example, we are exploring hybrid sketch summarization methods that attempt to combine both temporal and spatial clustering. Finally, because sketching is a meaningful way for designers to engage in dialogue with their ideas, we intend to study how selection and transformation operations suggest new interpretations to the designer.

8 CONCLUSION

In this paper, we studied the physical and cognitive operations involved in merging parts of existing sketches into a new sketch. In addition to the physical operations of selection and transformation, we identified four cognitive operations: reuse, refactor, repurpose and reinterpret that influence divergent thinking. We studied selection operations through a freeform selection tool and an object-select tool that uses a stroke-level aggregation method that combines strokes based on their temporal order. To study the effects of these factors on divergent thinking, we conducted a user study where participants were given a set of design tasks that involved functional and exploratory merge tasks. We scored the merged sketches through a crowdsourced survey, and coded each sketch with the cognitive operations used. Though the freeform selection technique was preferred by participants, we also identified potential uses of object selection, with an appropriate clustering metric. The scores from the survey for sketches produced in exploratory merge tasks were negatively correlated with the number of reuse operations, and positively correlated with the number of reinterpret operations. These results show that these cognitive operations determine the extent of exploration of the design space. We close with suggestions on further analyses and outline implications of our findings for HCI in sketching.

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REFERENCES

[1] S. K. Badam, S. Chandrasegaran, N. Elmqvist, and K. Ramani. Tracing and sketching performance using blunt-tipped styli on direct-touch tablets. In *Proceedings of the ACM Conference on Advanced Visual Interfaces*, pp. 193–200, 2014.

[2] M. A. Boden. *Dimensions of creativity*. MIT Press, 1996.

[3] B. Buxton. *Sketching User Experiences: Getting the Design Right and the Right Design*. Morgan Kaufmann, 2007.

[4] Q. Chen, J. Grundy, and J. Hosking. An e-whiteboard application to support early design-stage sketching of UML diagrams. In *Proceedings of the IEEE Symposium on Human Centric Computing Languages and Environments*, pp. 219–226, 2003.

[5] J. Dorsey, S. Xu, G. Smedresman, H. Rushmeier, and L. McMillan. The mental canvas: A tool for conceptual architectural design and analysis. In *Proceedings of the Pacific Conference on Computer Graphics and Applications*, pp. 201–210, 2007.

[6] E. S. Ferguson. *Engineering and the Mind's Eye*. MIT press, 1994.

[7] M. Gantt and B. A. Nardi. Gardeners and gurus: patterns of cooperation among cad users. In *Proceedings of the ACM Conference on Human Factors in Computing Systems*, pp. 107–117, 1992.

[8] F. Geyer, J. Budzinski, and H. Reiterer. IdeaVis: a hybrid workspace and interactive visualization for paper-based collaborative sketching sessions. In *Proceedings of the Nordic Conference on Human-Computer Interaction*, pp. 331–340, 2012.

[9] A. K. Goel and S. R. Bhatta. Use of design patterns in analogy-based design. *Advanced Engineering Informatics*, 18(2):85–94, 2004.

[10] A. K. Goel and S. Craw. Design, innovation and case-based reasoning. *The Knowledge Engineering Review*, 20(03):271–276, 2005.

[11] V. Goel. *Sketches of thought*. MIT Press, 1995.

[12] G. Goldschmidt. The dialectics of sketching. *Creativity Research Journal*, 4(2):123–143, 1991.

[13] J. Hailpern, E. Hinterbichler, C. Leppert, D. Cook, and B. P. Bailey. TEAM STORM: demonstrating an interaction model for working with multiple ideas during creative group work. In *Proceedings of the ACM Conference on Creativity & Cognition*, pp. 193–202, 2007.

[14] D. G. Jansson and S. M. Smith. Design fixation. *Design studies*, 12(1):3–11, 1991.

[15] I. Jowers and C. Earl. Shape interpretation with design computing. In J. Gero, ed., *Design Computing and Cognition'12*, pp. 343–360. 2014.

[16] L. B. Kara and K. Shimada. Supporting early styling design of automobiles using sketch-based 3D shape construction. *Computer-Aided Design & Applications*, 5(6):867—876, 2008.

[17] N. Kelly and J. S. Gero. Generate and situated transformation as a paradigm for models of computational creativity. *International Journal of Design Creativity and Innovation*, pp. 1–19, 2016.

[18] M. Knobel and C. Lankshear. Remix: The art and craft of endless hybridization. *Journal of Adolescent & Adult Literacy*, 52(1):22–33, 2008.

[19] J. Kolko. Abductive thinking and sensemaking: The drivers of design synthesis. *Design Issues*, 26(1):15–28, 2010.

[20] R. H. McKim. *Experiences in Visual Thinking*. Brooks/Cole Pub. Co, Monterey, CA, 1972.

[21] F. L. McKoy, N. Vargas-Hernández, J. D. Summers, and J. J. Shah. Influence of design representation on effectiveness of idea generation. In *Proceedings of the ASME Design Engineering Technical Conference*, pp. 39–48, 2001.

[22] M. Michalko. *Thinkertoys: A Handbook of Creative-Thinking Techniques*. Ten Speed Press, 2010.

[23] W. J. Mitchell. A computational view of design creativity. *Modeling Creativity and Knowledge-Base Creative Design*, pp. 25–42, 1993.

[24] L. Oehlberg, W. Willett, and W. E. Mackay. Patterns of physical design remixing in online maker communities. In *Proceedings of the ACM Conference on Human Factors in Computing Systems*, pp. 639–648, 2015.

[25] M. Prats, S. Lim, I. Jowers, S. W. Garner, and S. Chase. Transforming shape in design: observations from studies of sketching. *Design Studies*, 30(5):503–520, 2009.

[26] S. Pugh. Concept selection: a method that works. In *Proceedings of the International Conference on Engineering Design*, pp. 497–506, 1981.

[27] M. Resnick, B. Myers, K. Nakakoji, B. Shneiderman, R. Pausch, T. Selker, and M. Eisenberg. Design principles for tools to support creative thinking. In *NSF Workshop Report on Creativity Support Tools.*, pp. 25–35. 2005.

[28] T. Salvador, J. Scholtz, and J. Larson. The Denver model for groupware design. *SIGCHI Bulletin*, 28(1):52–58, 1996.

[29] U. B. Sangiorgi, F. Beuvens, and J. Vanderdonckt. User interface design by collaborative sketching. In *Proceedings of the ACM Conference on Designing Interactive Systems*, pp. 378–387, 2012.

[30] E. Saund, J. Mahoney, D. Fleet, D. Larner, and E. Lank. Perceptual organization as a foundation for intelligent sketch editing. In *AAAI Spring Symposium on Sketch Understanding*, pp. 118–125, 2002.

[31] E. Saund and T. P. Moran. A perceptually-supported sketch editor. In *Proceedings of the ACM symposium on User Interface Software and Technology*, pp. 175–184, 1994.

[32] J. J. Shah, N. Vargas-Hernandez, J. D. Summers, and S. Kulkarni. Collaborative sketching (c-sketch)–an idea generation technique for engineering design. *Creative Behavior*, 35(3):168–198, 2001.

[33] M. Suwa, B. Tversky, J. Gero, and T. Purcell. Seeing into sketches: Regrouping parts encourages new interpretations. In *Visual and Spatial Reasoning in Design*, pp. 207–219. 2001.

[34] D. G. Ullman, S. Wood, and D. Craig. The importance of drawing in the mechanical design process. *Computers & Graphics*, 14(2):263–274, 1990.

[35] A. B. VanGundy. *Techniques of structured problem solving*. Springer, 1988.

[36] S. Zabramski and S. Neelakannan. Paper equals screen: a comparison of a pen-based figural creativity test in computerized and paper form. In *Proceedings of the Conference on Creativity and Innovation in Design*, pp. 47–50, 2011.

[37] D. Zahner, J. V. Nickerson, B. Tversky, J. E. Corter, and J. Ma. A fix for fixation? rerepresenting and abstracting as creative processes in the design of information systems. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 24(02):231–244, 2010.

[38] Z. Zhao, S. K. Badam, S. Chandrasegaran, D. G. Park, N. Elmqvist, L. Kisselburgh, and K. Ramani. skWiki: A multimedia sketching system for collaborative creativity. In *Proceedings of the ACM Conference on Human Factors in Computing Systems*, pp. 1235–1244, 2014.

[39] Z. Zhao, W. Benjamin, N. Elmqvist, and K. Ramani. Sketcholution: Interaction histories for sketching. *International Journal of Human-Computer Studies*, 82:11–20, 2015.