The Influence of Digital Sketching Tools on Concept Novelty and Evolution

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Digital tools for sketching, such as tablets, have become popular for streamlining design work and keeping a large quantity of sketches in one place. However, their impact on design creativity, novelty, and concept evolution is not yet well understood. Here, we present a controlled human subjects study that assesses the influence of tablets (iPads) on concept novelty and evolution in the context of an engineering design concept generation exercise. We expect that iPad use will not influence concept novelty due to its similar speed of use as pen and paper sketching. We expect to see different patterns in concept evolution between the two types of tools, namely, that iPad users will demonstrate more iteration on a concept (concept evolution) than pen and paper users due to the fact that iPad features make it easy to copy and paste previous sketches and then modify them. We find that the tool used is not correlated with concept novelty. Additionally, we find no strong differences in overall concept evolution quantities between the two tools, though we see that iPad sketches exhibited more cases of consecutive concept evolution than nonconsecutive whereas paper and pen sketches showed an equal amount of both consecutive and nonconsecutive concept evolution. Results indicate that overall, iPads may not significantly inhibit designers' creative skills and thus could be a reasonable replacement for pen and paper sketching, which has implications for both design education and practice.
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Keywords: creativity and concept generation, design evaluation, design methodology, design process, design representation, design theory, design theory and methodology, design visualization, product design

1 Introduction

Sketching is a fundamental component of early stage engineering design as it allows designers to quickly visually represent their concepts, think through their ideas, and communicate concepts to others [1,2]. A majority of life cycle costs in the design process are determined by decisions made during these early stages of design, so changes to these stages may influence the eventual cost and performance of designed artifacts [3]. As remote work has become popular in both education and industry, digital design tools have gained popularity [4,5]. Tablets are now a popular medium for sketching and taking notes and offer the ability to keep all documents in a single place [5]. However, tablets as a design tool are relatively new and have not been studied in depth [4,5]. As new tools are used by designers, it is crucial to study the influence these tools have on the design process. In particular, if tablets afford particular benefits to designers in terms of improved creativity or better design outcomes, there are strong implications for equity in the design process. Existing discrepancies in access to digital tools could have larger impacts for design teams and lead to exacerbated inequities in the design process.

In an effort to expand the discipline's understanding of how tablet use may influence the design process, we are conducting a series of studies investigating differences in ideation sketch attributes between tablets and paper/pen. Our prior work has investigated how sketch quality and quantity is impacted by the tools used for a short high-level brainstorming session [5] as well as a more detailed engineering concept generation task [4]. In particular, we have found that the quantity and understandability of sketches made between tools stays constant while the quality of sketches made using iPads is lower than that of those made with pen and paper [4]. However, there have not yet been studies exploring differences in content or novelty of ideas generated using each medium. Similarly, very few studies have examined ways in which designers' ideas evolve throughout the ideation process even when simply sketching on paper [6]. These aspects of the ideation process are important to understand, especially if the use of tablets leads to different results.

During these early stages of design, creativity is a crucial part of the process and much work has been done to try and determine how to promote and assess creativity in design processes [7,8]. One way to approximately quantify creativity is by assessing the novelty of a concept [9]. In this study, we focus on understanding how concept novelty and concept evolution, or the way concepts are iterated on

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and improved over the course of the idea generation, are impacted by the tool used during an engineering concept generation task. Since tablets have some built in features such as copy/paste and erasing that facilitate quick iteration, we may expect to see that these features allow designers to easily iterate on an idea and improve it. At the same time, this type of detailed development may come at the expense of exploring the full design space with a variety of novel ideas by keeping designers more focused on a single path of ideation rather than focusing on flexibility [10]. The impact of these features may manifest as tablets affording a better experience for design evolution but a worse one for concept novelty.

2 Related Work

2.1 Early Stage Concept Sketching. Sketching is a fundamental part of early stage engineering design processes [8,11–14]. Sketch quantity, not quality, is linked with better design outcomes [15–17]. However, higher quality sketches have been found to be perceived as more creative than lower quality sketches [18,19]. When investigating the differences between early stage concept sketching on paper versus on tablets, prior work has found that the quality of sketches made using iPads is lower than that of those made with pen and paper though the quantity of ideas is the same [4]. This may imply that pen and paper sketches may be perceived as more creative. Hence, it is important to assess how sketch creativity or novelty is linked with the tool used to create the sketch as it may have implications for how these tools should be used by designers.

2.2 Use of Digital Tools in Design. Immersive digital design tools can assist with visual thinking, but many digital tools can be costly and impractical for use [20]. Tablets are relatively less expensive than some other digital tools and have become popular for sketching purposes since designers are able to carry all their files in one place and emulate a variety of sketching tools without having to own different kinds of pens and pencils [21]. The compact, portable nature of tablets coupled with increasingly sophisticated apps for drawing makes them a powerful alternative to traditional pen and paper for sketching and design. Some designers have reflected on their own personal use of these devices for sketching [22]. Educators have even explored tablets as an alternative to design sketchbooks as a record of students' design processes [23].

While minimal work has been found that explicitly examines the widespread adoption of tablets in the context of sketching and design teams, studies show that tablets have been becoming more integrated in the daily lives of individuals [24,25]. As Lee et al. note, the rate of adoption for tablets has grown quickly and at times even outpaced that of many other technologically advanced devices, including smartphones [25]. Users appreciate their versatility and the convenience they offer for tasks ranging from media consumption to digital artwork creation. Furthermore, a study by Ozkale and Koc on tablet use in academicians found that the devices are overwhelmingly popular [24]. Among their participants, the majority carried their tablets everywhere and used them on a daily basis [24]. Consequently, the choice of tablets for our study is motivated by the potential for their eventual ubiquity in the design process and the relative lack of studies regarding their current influence on the design process.

Other digital design tools have been more extensively studied and prior studies have shown that some such as computer aided design (CAD) can lead to design fixation and reduced creativity if they are used too early in the design process [26,27]. Tablet sketching is relatively lower fidelity than CAD but still allows designers to beautify their sketches and focus on perfecting elements of their drawings to make them appear more refined such as by creating straight lines and perfect shapes or easily adding color and shading [28,29]. Since design creativity and novelty are essential to the early design process, it is important to investigate whether or not the use of digital design tools impacts the design's novelty especially since more refined sketches may be perceived as more creative [18]. The results of this work may have insights for both engineering education and engineering practice, especially in terms of best practices for early stage sketching.

2.3 Sketch Novelty. Novelty has been used as a measure of the uniqueness of an individual concept within a pool of ideas. Shah proposed novelty as one of four criteria for measuring effectiveness of ideation, with the others being variety, quantity, and quality [9]. Shah defined two methods for evaluating novelty: "a-priori" where solutions that are not novel are defined before any data are reviewed to avoid biasing and "a-posteriori" where ideas are categorized by key attributes, such as control mechanism or actuation method, and each subgroup is evaluated by the frequency of the category [9]. A modified version of the "a-posteriori" method is used here.

Weaver et al. compared three novelty measures in analyzing test-based ideation data [30]. Weaver grouped ideas into "bins" of similar ideas and then calculated novelty as a "relative infrequency." This was found to be a valid form of calculating novelty when compared with other novelty assessment metrics [30]. As a result, this is the methodology used in this study.

2.4 Concept Evolution Theory. Within design theory, Maher's work on co-evolution provides a relevant framework for understanding how sketching and ideation might be affected by the tools used [31]. This model of co-evolutionary design suggests an intertwined development of the problem space and the solution space where the design problem and solution co-evolve, each influencing and shaping the other iteratively as the design process progresses [31]. This co-evolutionary model promotes creativity, innovation, and the generation of novel solutions [31].

Sketching can serve as a vital dialogue that facilitates this iterative co-evolutionary process [15,32]. As designers sketch, they are simultaneously exploring, understanding, and defining the problem, which feeds back into the co-evolutionary model and informs new ideas and solutions [15,32]. Prior work on idea evolution has also found that evolved iterations of ideas tend to be more novel than initial sketches [6]. In light of the transition to and greater adoption of digital tools, understanding how this new context influences the evolution of design concepts during the iterative sketching process is crucial.

2.5 Study Contribution. Tablet use during early stage engineering design ideation has been minimally studied thus far. In particular, the impact of tablet use on the novelty of sketches produced and the concept evolution process of designers during ideation has not yet been explored despite the potential implications for enhancing or stymieing creativity during ideation. This study seeks to add to the understanding of sketching in engineering design by exploring the influence that tablets have on the creative process via their impact on concept novelty and on concept evolution patterns.

3 Research Questions and Summary

RQ1: To what extent does sketching on a tablet impact the novelty of concepts generated during early stage engineering design?

This question asks about the impact of digital sketching on novelty. It is motivated by research suggesting that introducing digital tools such as CAD too early in the design process can result in design fixation and lower novelty [26,33]. Hand sketching on a digital tablet is generally as fast as sketching by hand on paper, so we hypothesize that tablet use will not result in inhibited novelty as iteration will be easier than iteration in CAD or other more time-intensive digital tools. We use a simplified version of Shah's

framework [5,9] to assess the novelty of concepts based on how frequently other participants used similar mechanisms in their ideas.

RQ2: To what extent does sketching on a tablet impact the design evolution of concepts during early stage engineering design?

This question aims to assess how the use of digital tools might influence concept evolution, or how an idea is iterated over time. Since tools like tablets allow users to perform actions such as copying and pasting, we hypothesize that it will be easier for designers to iterate on and improve their concepts. Because of this, we expect that sketches from designers using tablets will exhibit more similarities to each other than sketches from designers using paper and that they may gravitate toward consecutive evolution of ideas (modifying concepts back to back) rather than returning to an idea later after exploring the design space. To explore this question, we assess how designers' ideas evolved over the course of their ideation process. By tracking sketches that build on participants' previous ideas and categorizing them based on the type of evolution (consecutive, nonconsecutive, or combined), we are able to understand potential impacts of the sketching tool used on participants' concept evolution patterns.

3.1 Summary. This study reports the results of an experiment with 40 participants who participated in a concept generation exercise for engineering design prompts using either pen and paper or a tablet (iPad) for sketching. The novelty of the concepts sketched was assessed and some case studies of concept evolution are presented. This work assesses the influence of the sketching tool on the concept novelty and investigates possible relationships between the sketching tool used and the way in which the designer's ideas evolve over the course of an ideation session.

4 Methods

4.1 Participant Recruitment. Forty undergraduate and graduate students affiliated with the Mechanical Engineering Department at a New England University were recruited for the study. This study focused on students instead of practitioners since the university instated a program starting in Fall 2020 to loan iPads to undergraduate students for use in their classes as well as graduate students who served as Teaching Assistants (TAs). As a result, many of the students had experience using or seeing others use these specific devices in their courses and day to day experience. Participants were compensated for their participation in the study with a gift of a sketching kit consisting of a canvas pouch with four sketching pens in it. As part of the recruitment process, participants filled out a pre-survey in advance with demographic questions and questions about their prior experience with digital and physical sketching tools.

The demographic breakdown of the participants is included in Table 1. The research population included a slightly higher percentage of women, with 22 women (55%) compared to 18 men (45%). The majority of participants in the study were graduate students, accounting for 27 (67.5%) of the total participants. However, the study also included undergraduate students from each year: four first-year students, five sophomores, three juniors, and one senior.

In terms of race and ethnicity, white participants made up the largest group with a total of 17 individuals. The second largest group was Asians with 15 participants, of which ten were East Asian and five were South Asian. There was one Black participant and one participant who identified exclusively as Hispanic/Latino. Six participants identified with multiple race/ethnicity categories, which included one individual who identified as white and Native American, three as white and Hispanic/Latino, and two as white and Middle Eastern or North African.

The study also tracked whether or not the students had participated in an iPad loaner program. Within this study, 16 of the participants had participated in the loaner program while 24 had not.

Additionally, participants self-reported their prior experience level with sketching tools on a scale from 0 to 10 with 0 signifying no experience with the medium and 10 denoting being very familiar with the medium. The distribution of these responses is shown in Fig. 1. Participants' experience level with traditional pen and paper sketching ranged from a low of 1 to a high of 10, with an average rating of 5.6. For digital sketching, the reported experience levels varied from a minimum score of 0 to a maximum of 8. The average rating was 4.1. In terms of digital notetaking, the participants' self-assessed experience levels spanned from 0 to 10, with an average rating of 6.1.

Table 1 Demographic data for all participants

Demographic	Category	Frequency	Percentage
Gender	Man	18	45%
	Woman	22	55%
Academic level	First-year	4	10%
	Sophomore	5	12.5%
	Junior	3	7.5%
	Senior	1	2.5%
	Graduate student	27	67.5%
Race/ethnicity	White	17	42.5%
	Asian		
	East Asian	10	25%
	South Asian	5	12.5%
	Multiple races/ethnicities		
	White and Native American	1	2.5%
	White and Hispanic/Latino	3	7.5%
	White and Middle Eastern or North African	2	5%
	Black	1	2.5%
	Hispanic/Latino	1	2.5%
iPad loaner program	Participated	16	40%
	Did not participate	24	60%

The 40 participants were randomly divided into four groups of ten for the study. Two groups sketched first on tablets and second with pen and paper and the other two groups sketched first with pen on paper and second on tablets. Within the two groups for each sketching tool, one group began with a milk frother prompt and the other group began with a peanut sheller prompt, as seen in Table 2. This allowed comparison of tablet and paper drawings while accounting for the ordering effect of which tool was used first. As a result, this study design accounted for potential effects of starting with either tool or either prompt, such as impacts on creativity and novelty.

4.2 Design Prompt Selection and Implementation. Each participant completed two concept generation exercises. These were selected based on their prior usage in the literature and were judged to be similar to each other in terms of level of difficulty [34–36]. Since this study focuses on novelty and concept evolution of ideas, only one prompt was chosen for the analysis since solutions to the two distinct problems cannot be compared to one another. The design prompt used was the milk frother problem which asks participants to ideate ways to froth milk (such as for a coffee drink) in a short time with minimal instruction and has been previously used to study creativity and design novelty [34,35].

Participants had 20 minutes to generate ideas for each prompt and were told to generate as many ideas as possible. The chosen timeframe was primarily informed by use of the prompts in prior literature [34–36], pilot testing of both prompts, and results from a previous study with a simpler prompt, which allowed participants only 5 minutes to brainstorm high-level conceptual ideas rather than dive into more detailed mechanisms [5]. The goal of this longer study was to observe how a longer time period affected sketch/design output, in particular whether any changes to sketch quality or novelty occur after an initial surge of inspiration runs

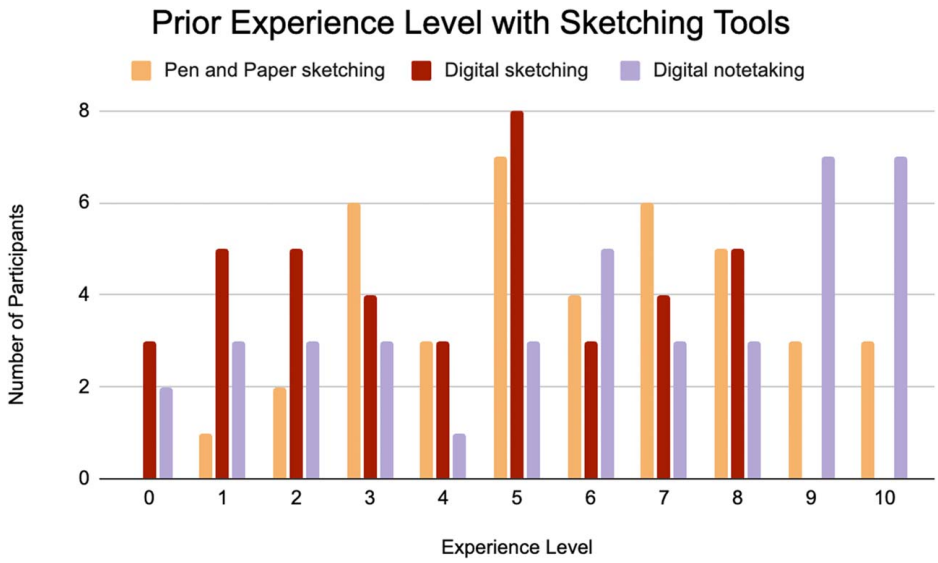

Fig. 1 Participants' self-reported prior experience with pen and paper sketching, digital sketching, and digital notetaking

Table 2 Experimental groups based on prompt and tool order

Group label	First prompt	Second prompt
A	Peanut sheller on paper	Milk frother on iPad
B	Peanut sheller on iPad	Milk frother on paper
C	Milk frother on paper	Peanut sheller on iPad
D	Milk frother on iPad	Peanut sheller on paper

out. Pilot testing was run using these prompts on multiple subjects in small group settings for a timeframe of 45 minutes, which was the longest time period used for these prompts in similar sketching exercises in prior literature [34–36], and found that participants generally ran out of ideas by the 15 min mark. Hence, 20 minutes was an appropriate time period that was slightly longer than the 15 min mark and would allow the entire experiment (two 20-minute ideation sessions in addition to the instructions and post-task survey) to be completed within 1 hour so as to avoid excessively fatiguing participants.

Again, for this study, only sketches from the milk frother design prompt are analyzed and described so as to be able to have consistent categories for novelty and design evolution in the context of the prompt. The full prompt for the milk frother exercise can be found in the Appendix.

4.3 Experimental Setup. The experiment was run by two researchers. They collected consent from all participants and then verbally read instructions for the experiment from a pre-written script. Participants sketched all ideas on the template shown in Fig. 2 and wrote a short caption or idea name in the appropriate spot on the template. This was particularly important as it helped ensure that assessments of novelty or creativity were focused on the novelty of the concept rather than creativity in the rater or judge's perception of an ambiguous concept. Participants were instructed to annotate the sketch as needed but were asked to primarily communicate the concept through the sketch rather than a written description.

At the end of the 20 min sketching period, participants were asked to fill out a post-task survey and were reminded not to share information regarding the exercise with others since the experiment was conducted over several weeks.

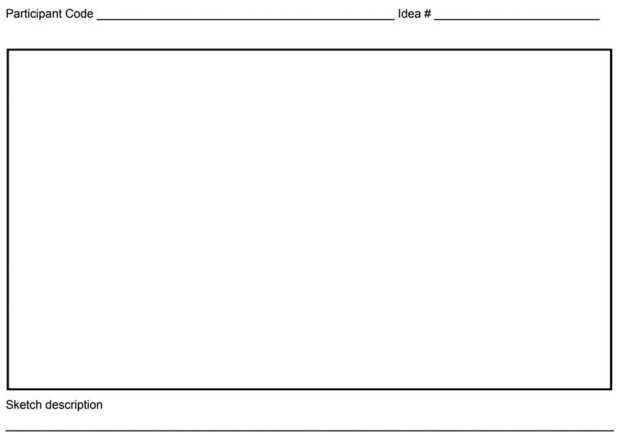

Fig. 2 Sketch template

4.3.1 Tablet Sketching Setup. All participants used an iPad with an Apple Pencil and sketched on the app "Notability."[2] Participants had access to all the features of the application and were not prevented from using any features. This application was chosen because the institution had a license for this software that made it free to use on the institutional iPads used for the experiment. Additionally, since the goal was to simulate early stage concept sketching on plain copy paper, an app that was geared toward note taking and sketching on a paper sized screen was the appropriate choice rather than apps that are designed for creating digital artwork. The vast majority (37 of 40 participants) had prior experience sketching on tablets. The iPad was preloaded with a 100 page sketching template (shown in Fig. 2) so that participants had a seemingly unlimited number of pages to sketch on. The features of the sketching application (such as changing pencil width, erasing, color changing, undo, copying and pasting, etc.) were briefly described, but not demonstrated, at the start of the exercise. Participants' screens were recorded to document their sketching process.

4.3.2 Pen and Paper Sketching Setup. For pen and paper sketching, all participants used a black fine line (0.4 mm) felt tip

[2]https://notability.com/

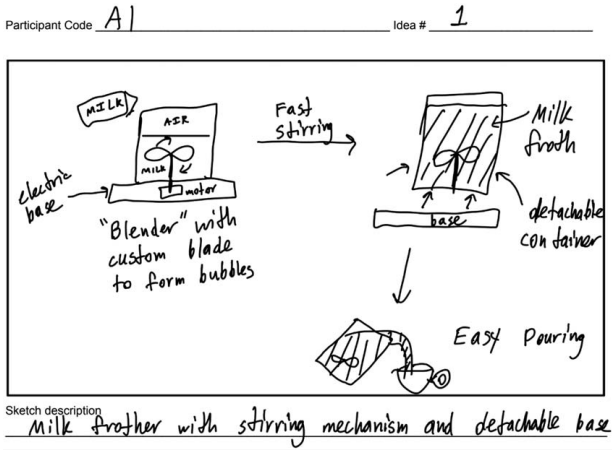

Fig. 3 Sketch representing the category of "radial spinning blades"

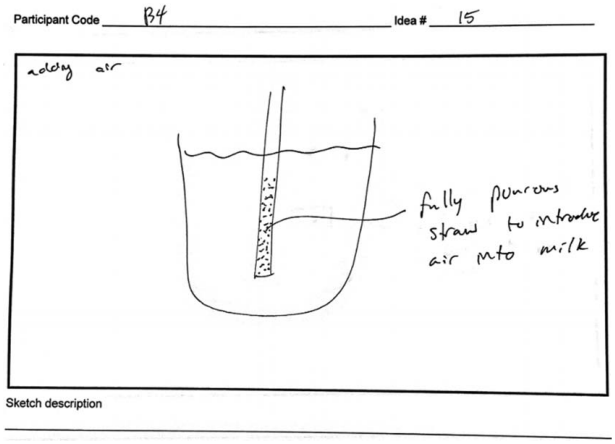

Fig. 4 Example of binning based on function

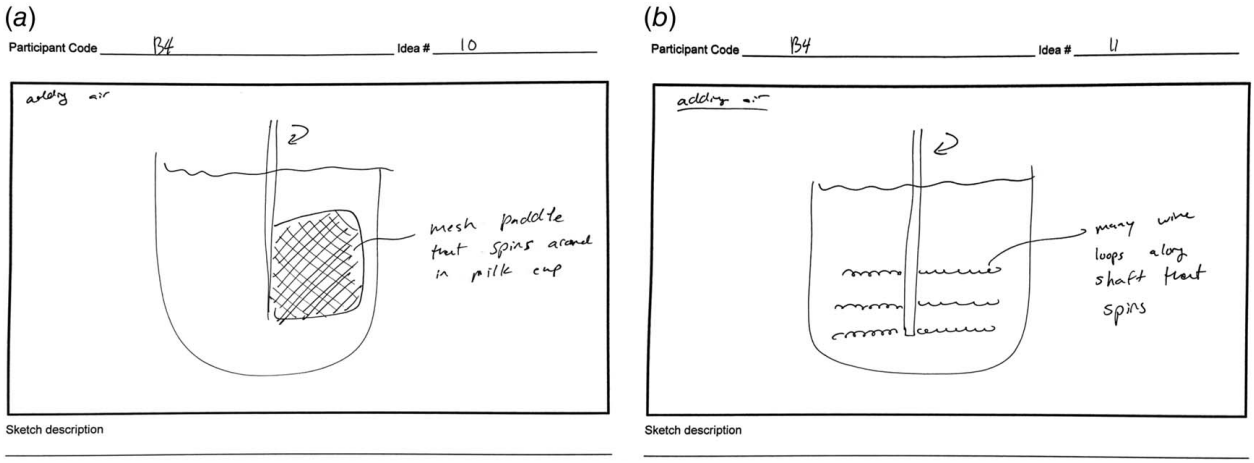

Fig. 5 Sketches (*a*) 10 and (*b*) 11 from participant B4, demonstrating consecutive concept evolution

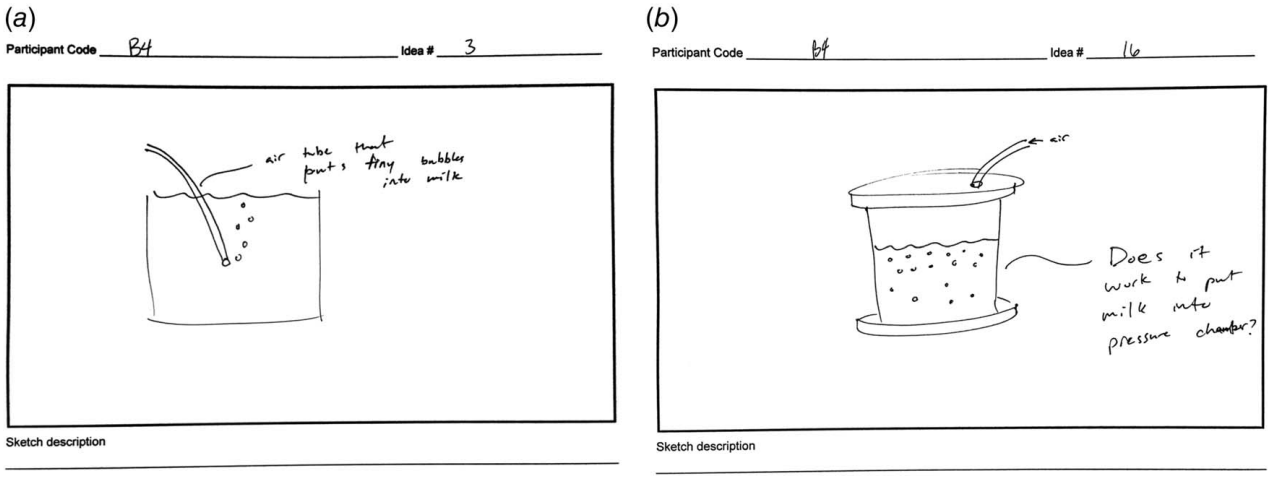

Fig. 6 Sketches (*a*) 3 and (*b*) 16 from participant B4, demonstrating nonconsecutive concept evolution

Sharpie pen (note: not a Sharpie marker) on white letter-sized copy paper printouts of the sketch template. This pen allows for a uniform line width and is designed to make dark, crisp lines that do not smudge, which also improves the ability to scan and analyze the images. Pen was used instead of pencil since it forces designers to commit to their lines instead of focusing on perfecting and refining them, which provides a clear contrast to the tablet features [5]. Participants were told that they would not be able to erase using this pen but that they could request another pen if they ran out of ink.

4.4 Novelty Analyses. The researchers recorded the text descriptions written by the participants along with any annotations in the image. A constructivist grounded-theory approach was then

Participant Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A1	A	B	C													
A2	A	B	C	D	E	F	G									
A3	A	A	B	C	D											
A4	A	B	C	D	E	F	G	H	I	J	K	L				
A5	A	B	C	A+C												
A6	A	B	C	D												
A7	A	B	C	D	E	F	G	H								
A8	A	A	B	C	C	D	E	F	F	G	H	I	J	K		
A9		A	B	C	D	E										
A10		A	B	C	D	E										
B1	A	B	C	D	E											
B2	A	B	C	D	E	F	G	H								
B3		A	B	C	D											
B4		A	B	C	D	E	F	B	G	H	H	I	I	J	K	B
B5	A	B	C	D	E	F	G									
B6	A	B	C	D	E	F	G	H	I							
B7	A	B	C	C	D											
B8	A	B	C	D	E	F	G		H	I						
B9	A	B	C	D	E	F										
B10	A	B	C	D	E	F	G	H								
C1	A	B	C	D												
C2	A	A	B	C												
C3	A	B	C	D	E	F	G									
C4	A	B	C	D	E	F	G	H	I	J	K	L	M			
C5		A	B	C	D	E	A	F	E	G	A					
C6	A	B	C	B	D	E	F									
C7	A	A	A	A	B	C	D	B	E							
C8	A	B	C	D	E	F	G	H								
C9	A	B	C	D												
C10	A	B	C	D	E											
D1	A	B	C	D												
D2	A	B	C	D	E	E	B	F	G							
D3	A	B	C	D	E	F	G	H	I	J	K					
D4	A	B	C	D	E	F	G	E	H	H	I	J	K			
D5	A	B	C	D	E	F	G	H	I	J	K	L	M			
D6	A	B	C	D	E	F	G	H								
D7	A	B	C	D	E	F	G									
D8		A	B	B	C	C	C	D								
D9	A	B	C	D	E	F	G	H	I							
D10	A	A	B	B	C											

Fig. 7 Concept evolution tracking diagram

used to qualitatively categorize the sketches based on these descriptions [37]. One researcher reviewed all images and descriptions in the dataset for the initial open coding step [38]. This resulted in 91 codes across the 308 images in the dataset. Next, these open codes were grouped into 43 axial codes (listed in the results) which served as the final bins for the images [5,30,38]. For instance, many drawings included features similar to blenders with spinning blades that extend radially, such as the one shown in Fig. 3. These were all labeled as "radial spinning blades."

Table 3 Final sketch description categories for milk frothing mechanisms and prevalence of each

Category	Description of category	Number of ideas
Pressurized air	Stream of pressurized air causes bubbles	38
Shaking	Container of milk is rapidly moved up and down or side to side	33
Radial spinning blades	Blades that are oriented along rotating axis	24
Axial spinning blades	Blades that are oriented perpendicular to rotating axis	20
Press/pump	Milk is agitated with a piston	19
Milk through spray/tube	Milk is forced or sprayed through small channel	17
Steam	Milk is heated with steam	14
Rotating cup	Container spins on its own axis	12
Filters	Milk is moved through container with porous layer(s)	10
Vibration	Milk is placed in vibrating container or surface	8
Frother	Solution references existing frother model	8
Mixing ball	Balls are included in container of milk to cause mixing	8
Chemical reaction	Bubbles are produced by chemical agent	8
Churning	Milk is mixed with a spiral auger	7
Wire loop	Solution references wire loop	6
Centrifuge/revolving	Container revolves on an external axis	5
Tilting	Container is inverted, partially or fully	5
Stirring	External object is used to stir milk	4
Carbonator	Reference of "soda stream" or CO_2	4
Nitrogen	Reference of "nitrogen" or N_2O	4
Gravity	Container of milk is dropped from a height	3
Wheel	Spinning wheel sits partially submerged in milk	3
Blades move up and down	Blades move in a piston motion	3
Boiling	Milk is brought to a boil	3
Ball with milk holder	Rolling ball features a compartment to hold milk	3
Froth inside cow	Cow is shaken or genetically modified to produce frothed milk	3
Explosive	Milk is agitated by explosion	2
Spiral	Milk is moved through spiral tube	2
Pressure chamber	Container of milk is pressurized	2
Spring plate	Container is placed on a platform on springs	2
Air flow	Passive air flow is directed into milk	2
Channel flow	Milk flow directed into paths	2
Espresso machine	Solution references espresso machine	2
Split flow	Milk flow is disrupted by an object	1
Fans	Fan flow is directed into milk	1
Throw-able container	Container of milk is thrown repeatedly	1
Microfluidics	Solution references microfluidics	1
Sonicater	Solution references sonicater	1
Thin film	Solution references thin film	1
Rotating rings	Driven rod with rings built into fixture	1
Electrolysis	Solution references electrolysis	1
Squeeze sponge	Milk is squeezed from a sponge manually	1
People splashing	People stand in vat of milk and splash	1

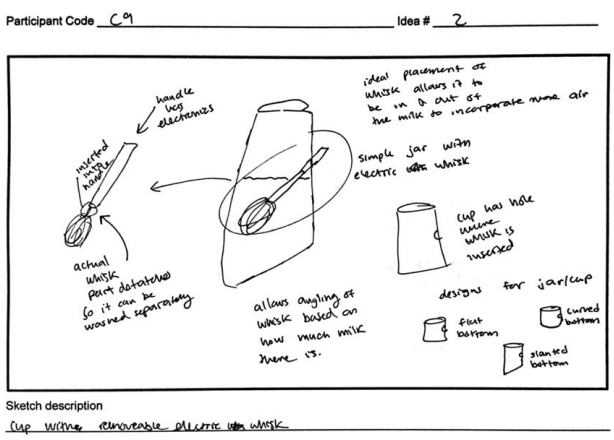

Fig. 8 Sketch representing the category of "axial spinning blades"

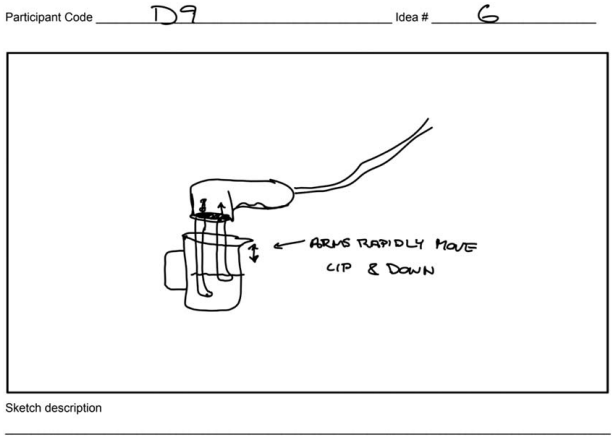

Fig. 9 Sketch representing the category of "blades moving up and down"

These categories were created by listing the distinct features included in each sketch and determining which feature was either most relevant to function or unique within the pool of ideas. Sketches that included combinations of two or more ideas, such as Fig. 4 which shows a "fully porous straw to introduce air into milk" being an example of both "Milk through spray/tube" and "Filters," required weighing between relevance to function and uniqueness. Usually, priority was given to relevance to function,

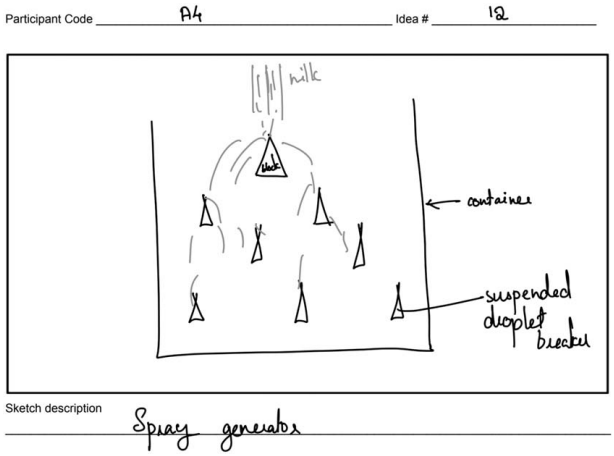

Fig. 10 Sketch representing the category of "split flow"

Table 4 Novelty score assignments

Number of ideas with same description	Assigned novelty score	Number of descriptions per novelty score	Number of sketches with novelty score
1–2	5	17	24
3–7	4	13	53
8–18	3	8	85
19–24	2	3	63
25+	1	2	71

and the sketch description and annotations were taken into account for determining designer intent. For instance, in Fig. 4, the sketch description is written on the image instead of on the line below the image, so looking at the annotations provides the relevant information. In this specific example, the idea was categorized as "Milk through spray/tube" due to the rater's interpretation that this feature is more directly necessary for the functionality of "adding air."

After these final bins were created, a second rater took a random sample of 20% of the total sketches and independently binned them into the final list of 43 bins to ensure agreement between the raters on the sketch binning. The two raters had 80% agreement on the binning.

This binning was used to determine novelty scores for each sketch using a simplified version of Shah's novelty metric [9] that was also used in our prior work [5]. The total number of sketches with each consistent description was counted and concepts were assigned novelty ratings from 1 (worst) to 5 (best) based on how many other sketches had the same consistent sketch description. The fewer sketches with the same description, the higher the novelty rating.

For this study, only concepts showing a frothing mechanism were counted. For instance, one participant drew several interfaces (a switch, a dial, etc.) that did not actually include the frothing mechanism. These concepts were not included in the dataset. Similarly, sketches of mind maps or other brainstorming tools that did not actually include a concept were not included.

4.5 Statistical Analyses. The Wilcoxon rank sum test was used to compare the novelty scores between the two tools as the data are unpaired and nonparametric. Results at the 5% significance level ($p < 0.05$) are considered to be statistically significant.

4.6 Concept Evolution Assessment. This study aimed to understand how designs evolved within each participant's set of sketches. For example, how does a participant's third sketch differ from their first one if both are categorized in the same descriptive category for novelty (such as both being labeled as "radial spinning blades")? The changes in ideas featuring similar mechanical components throughout the brainstorming process—such as function, features, or appearance—were analyzed. In this study, we refer to this kind of change as the "evolution" of the concept.

Table 5 Summary of consecutive and nonconsecutive evolution results

	Tablet participants	Paper participants	Tablet instances	Paper instances
Consecutive only	4	2	11	5
Nonconsecutive only	0	2	2	5
Mix of consecutive and nonconsecutive	2	2	N/A	N/A
Combining ideas	1	0	1	0

Note: The results are split both by number of participants and instances of each type of concept evolution for each tool.

A specific area of interest in this study was the presence of consecutive and nonconsecutive evolution in the sketches. The consecutive nature of concept evolution is interesting because of the visual differences in tablet and paper sketching. Paper sketching allows designers to see several of their sketches at once, if they so desire. Tablet sketching in this context (a notetaking/sketching application rather than a whiteboarding application) essentially forces designers to look at one sketch at a time or look at the sketches in chronological order, so it may be more likely that any iteration on a concept is related to the most recent sketch that was made.

Consecutive concept evolution refers to sketches bearing similar aspects or core ideas to the one sketched immediately prior. Nonconsecutive concept evolution refers to sketches bearing similarities to sketches made more than one page prior. One example of each type of concept evolution from a single participant is shown here in order to further visualize the process.

Ideas 10 and 11, shown in Fig. 5, illustrate similar ideas, with the only difference being a different rotating attachment to help froth the milk. This shows consecutive concept evolution, where the improved or changed idea is drawn immediately after the initial sketch.

Ideas 3 and 16, shown in Fig. 6, also show concept evolution, as they both use an air tube that blows bubbles in the milk, but the second iteration appears long after the initial sketch. In sketch 16, the participant adds the idea of the milk being in a pressurized chamber to produce better froth, showing nonconsecutive concept evolution from sketch 3.

A concept evolution analysis was conducted on the complete dataset of milk frother sketches by tracking instances of concept evolution in a spreadsheet, as depicted in Fig. 6. In this study, our tracking of concept evolution was primarily focused on three categories: similarities in the frothing mechanism (i.e., both ideas use a mixer ball), situations where it is clear that the participant is building off of a previous sketch because they have used a very similar overall sketch (this was primarily seen in iPad users due to their ability to copy and paste), or in situations where a participant combined two previous ideas. This categorization was done by one researcher with discussion between two researchers for particular instances where the form of concept evolution was non-obvious. After this categorization was done, a second rater (different from the one who participated in the initial rating discussion) took a random sample of 20% of the total sketches and independently categorized them using the same setup. The two raters had 96% agreement on the categorizations of each individual sketch and 86% agreement on whether or not there were instances of concept evolution.

In Fig. 7, the participant code column lists all 40 participants, and cells highlighted in gray indicate that the participant used an iPad for the prompt, while white cells indicate that the participant used

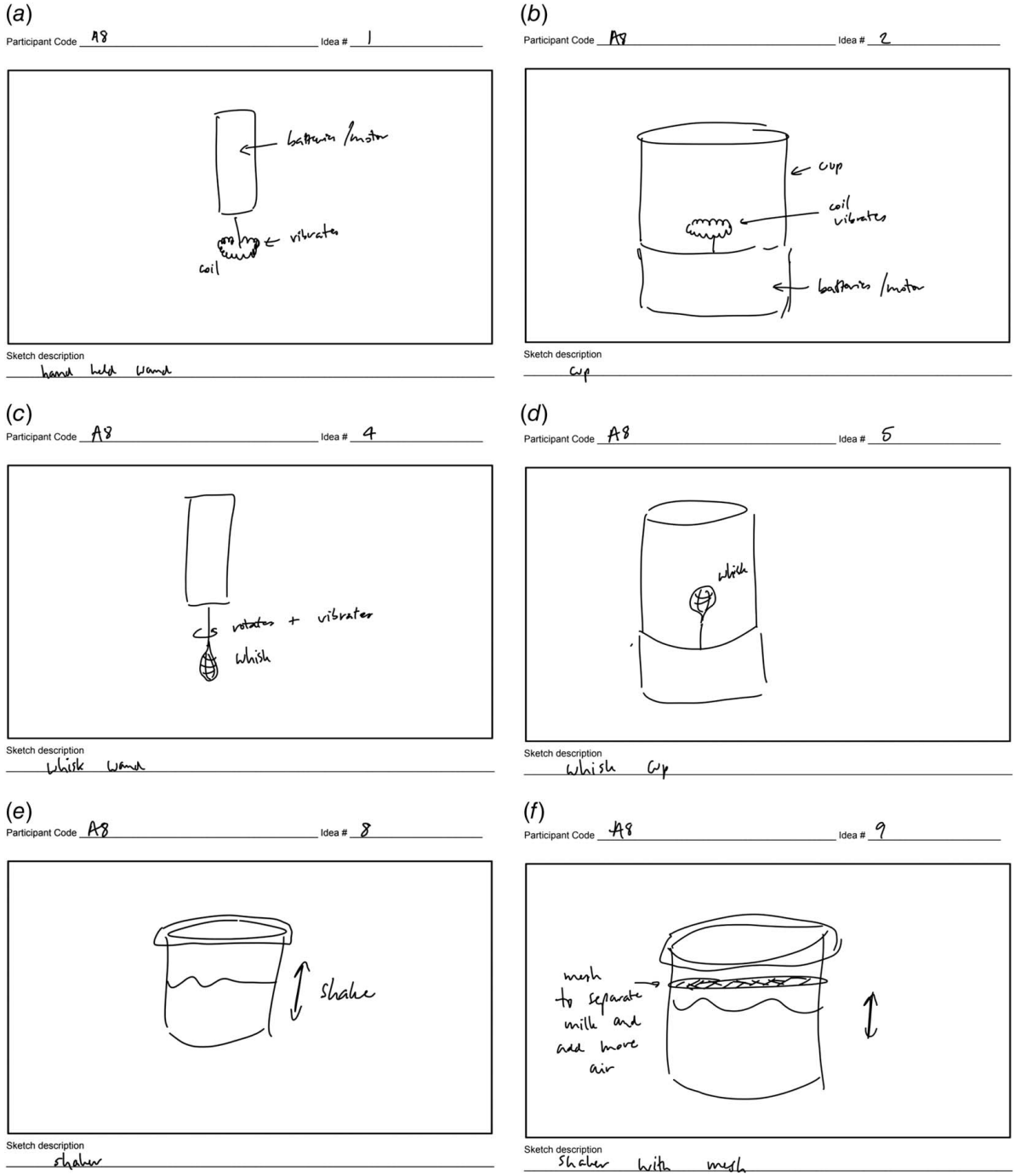

Fig. 11 Sketches (*a*) 1, (*b*) 2, (c) 4, (*d*) 5, (e) 8, and (*f*) 9 from participant A8 showing their concept evolution patterns

paper. The numbers in row 1 indicate the page number of the sketch, since each sketch takes up one full page. Each sketch is marked with a letter, and black cells indicate that the participant used the page for purposes other than sketching, such as mind mapping or listing potential ideas to aid the sketching process. Different letters represent unique sketch ideas per each row. If two cells have the same letter, that means the sketches show some evidence of concept evolution. All instances of evolution have been highlighted in dark gray, and examples of consecutive evolution are grouped and outlined for enhanced visibility. Tracking the concept evolution in all of the sketches in this manner provides an effective way to easily see when participants showed consecutive evolution or nonconsecutive evolution. In one case, a participant (A5) explicitly stated that they combined two previous ideas, so their fourth sketch is marked with the letters of the sketches used to generate the new idea. Two out of their three sketches show consecutive evolution, and two out of three show nonconsecutive evolution. This "combination" under concept evolution is treated as its own category, and it serves as an interesting example of having both consecutive and nonconsecutive evolution within the same idea cluster.

5 Results

5.1 Sketch Novelty

5.1.1 Sketch Categories. There were 43 final description categories (bins) established, which are listed in Table 3 along with how many ideas fell into each category.

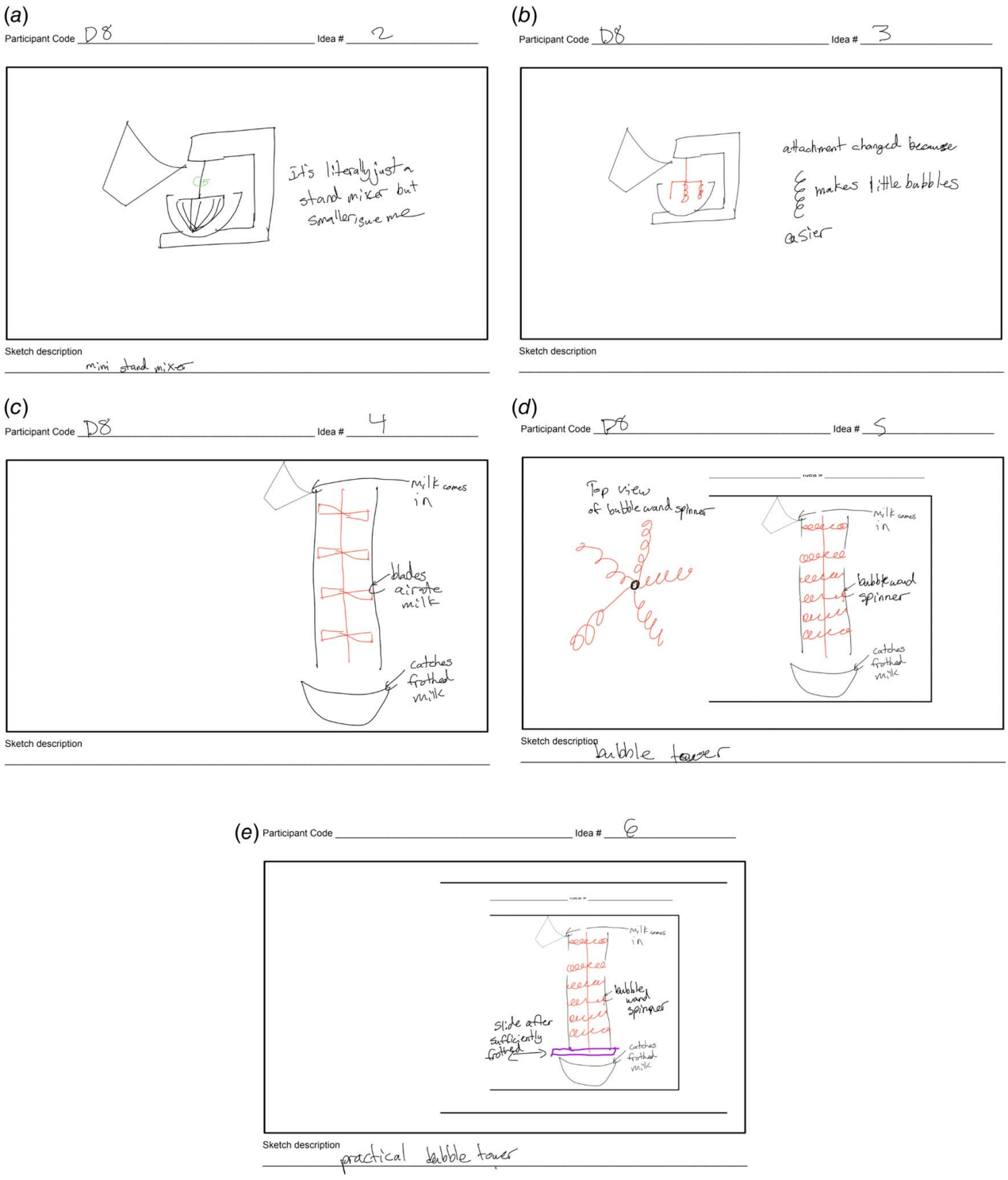

Fig. 12 Sketches (*a*) 2, (*b*) 3, (c) 4, (*d*) 5, and (e) 6 from participant D8 showing their concept evolution patterns

Examples of some of the idea descriptions are shown below. These sketches were categorized as axial spinning blades (Fig. 8), blades moving up and down (Fig. 9), and split flow (Fig. 10).

Then, the number of ideas with the same description was tabulated and assigned novelty scores based on natural break points in the dataset where the number of ideas with the same description shifted or jumped to a new level. There was an effort made to have the median score be 3 in order to have a relatively centered distribution. The final table of novelty score assignments is shown in Table 4.

5.1.2 Novelty Scores By Design Tool. There were no statistically significant differences in novelty scores ($p = 0.693$) between the iPad sketches and paper and pen sketches. The mean novelty score for iPad sketches was 2.68 and the mean novelty score for paper sketches was 2.62.

5.2 Concept Evolution. Overall, sketchers who used pen and paper exhibited both consecutive and nonconsecutive concept evolution in equal amounts, while tablet users showed a slight inclination for consecutive evolution.

Out of the 40 participants in this study, 13 showed at least one case of concept evolution. Seven were iPad users and six were paper users, showing a relatively even split with no clear evidence of either paper or iPad affecting one's proclivity for concept evolution overall. However, an interesting distinction can be made in whether the concept evolution was consecutive or nonconsecutive, as shown in Table 5.

Within the six paper users, two showed exclusively consecutive evolution, two showed exclusively nonconsecutive, and two showed both types of evolution. In total, there were five instances of consecutive and five instances of nonconsecutive evolution. However, out of the seven iPad users, four showed solely consecutive evolution, zero showed solely nonconsecutive evolution, and two showed both types of evolution. One iPad participant also combined two ideas rather than iterating on a single type of concept. Overall for the iPad group, there were 11 cases of consecutive evolution, two cases of nonconsecutive evolution, and one case of combined evolution. Although this study had a relatively small sample size of participants demonstrating concept evolution, these initial results suggest that iPad users may have a greater tendency to exhibit consecutive evolution than nonconsecutive evolution. To further understand this pattern, a Fisher's exact test was used to analyze whether or not there is a nonrandom correlation between evolution type and tool used. For the test, the number of instances of each type of evolution per tool was used. The Fisher exact test statistic value is 0.1688, which is not statistically significant at $p < .05$. However, the sample size here is very small and so further study is needed in order to better understand these patterns quantitatively.

Several examples of participants' concept evolution patterns are described qualitatively in further detail below. Participant A8 often had two adjacent ideas with the same core component or concept, as shown in Fig. 11. Ideas 1 and 2 use the same vibrating coil tool, but idea 1 uses it in a handheld motor form and idea 2 has it at the bottom of a motorized cup. Ideas 3 and 4 are very similar, having the same progression from handheld device to cup but using a whisk instead of a coil. Ideas 8 and 9 progress from a handheld shaker to one with mesh to help the frothing process. This was a common theme: several other participants also came up with a shaker idea and then added or changed one aspect of it in the next sketch.

One feature of the iPad that encouraged concept evolution was the ability to copy and paste elements of a sketch. Participant D8's sketches, shown in Fig. 12, are a demonstration of this feature. There are several instances where this participant copied and pasted a previous sketch to add something new to the idea. The first instance is a stand mixer sketch in idea #2 which they then pasted into idea #3, changing only the attachment in the stand mixer. The second instance is a series of small changes made to the same general bubble tower idea in which milk is poured from the top onto layers of rotating frothers with one aspect changed about the sketch each time.

6 Discussion

6.1 Concept Novelty. The lack of a statistically significant difference in novelty scores between iPad and paper drawings suggests that the use of iPads may not improve nor hinder the novelty of concepts sketched during the concept generation process. This has remarkable implications for the field because it implies that the use of iPads is a reasonable alternative to paper and pen for early stage sketching in terms of how it might influence the novelty of ideas. If iPads continue to become more commonly used for early stage design, design exercises and processes may become more sustainable simply through the use of less paper. Current processes encourage the use of many sheets of paper in an effort to draw at a large scale and keep one idea to a page. These same best practices can be followed while drawing on tablets without using up reams of physical paper [39,40].

6.2 Concept Evolution. Overall, it appears that there may be a difference in concept evolution patterns between paper and tablet, though the sample size in this study was small and results are not statistically significant. Paper and pen results had a higher proportion of nonconsecutive concept evolution than iPad. This may mean that iPads are well suited to iterating on a concept while paper and pen are better suited for exploring the full design space. Both of these types of ideation are important. Prior work has found that more evolved ideas are more novel [6] and research has also shown that having a large quantity of ideas is also linked with having better, more creative ideas [8]. It is possible that a combined use of the two tools could result in a set of ideas that spans the breadth and depth of the design space.

While we cannot yet make a value judgment about whether consecutive or nonconsecutive concept evolution is more desired during these early stages, it is notable that there is a potential difference in concept evolution patterns when it comes to the use of digital design tools such as tablets and this difference should be studied further. Further research must be done to directly investigate this potential difference and see whether any clearer patterns emerge that can help practitioners determine which tools are most appropriate for different phases of ideation.

7 Conclusions

Overall, it appears that the use of tablets for sketching does not have a significant impact on the novelty of concepts generated during ideation for engineering design problems, but the tool used does appear to influence concept evolution patterns.

RQ1: To what extent does sketching on a tablet impact the novelty of concepts generated during early stage engineering design?

No statistically significant difference in sketch novelty scores was found between sketches made on tablets and sketches made using pen and paper.

These findings indicate that the novelty of sketches remains consistent regardless of whether a tablet or traditional pen and paper are used for sketching, which is in line with our previous work that finds no difference in quantity and understandability of sketches produced between the two tools [4]. This absence of significant differences suggests that, at least in terms of novelty, quantity, and understandability, tablets may serve as an effective replacement for traditional pen and paper sketching techniques [4]. The novelty results combined with our prior work provide further evidence that the widespread adoption of tablets in the design industry may be a reasonable direction moving forward. The tablet's similarity to paper sketching in these ways confirms our hypothesis that tablet use will not result in inhibited novelty despite being a digital tool, unlike higher-fidelity tools such as CAD [26,41]. This finding holds considerable relevance in our contemporary context, as tablets continue to gain traction and may soon become the predominant tool for sketching within the design industry.

RQ2: To what extent does sketching on a tablet impact the design evolution of concepts during early stage engineering design?

Tablet sketching does not appear to have a significantly different impact on the overall amount of concept evolution, though it is clear that the feature of tablets to copy and paste previous sketches to build on them makes iterating on ideas easier as seen in several participants' sketches. The results presented here show some initial differences between evolution patterns in the two forms of sketching. In particular, concept evolution with iPad sketching was observed to have greater levels of consecutive evolution than nonconsecutive evolution while paper sketching had equal cases of consecutive and nonconsecutive evolution.

These differences in patterns of concept evolution between the two tools warrant further investigation. The fact that there seems to be greater levels of consecutive evolution than nonconsecutive in tablets whereas the instances of consecutive and nonconsecutive evolution on paper are equal could affect a part of the design process that was not observed in this study. Understanding how

concept evolution patterns influence eventual design outcomes is an important next step to determine whether or not the difference in consecutive/nonconsecutive evolution is important to the design process as a whole. Nonconsecutive evolution may have the potential to lead to unexpected or innovative solutions, so there may still be value in retaining traditional sketching methods alongside digital ones for certain tasks or stages of the design process. For developers of sketching and design software, these findings may also guide feature development. For instance, future iterations of sketching software could include features that better facilitate nonconsecutive evolution such as by making it easier to digitally "spread out pieces of paper," which could assist in addressing the current observed difference between tools. This would help retain the benefits of tablet sketching such as compactness and portability while emulating the potential benefits of paper sketching.

Despite similar novelty scores between tablet and paper sketching, the presence of concept evolution in the design process may have implications for differences in design fixation between the two tools. The evolution of concepts may be similar to the branches of a mind map, where designers may make multiple new and unrelated branches or add to an existing branch [42]. While continuing down existing branches may lead to more detailed and developed ideas, it could also indicate a lack of flexible thinking [10]. There are many trade-offs between detailed development and exploration of the full design space, so the implications of concept evolution patterns on the design process requires deeper understanding and further investigation, with a focus on these patterns' potential to influence flexibility in design.

8 Limitations and Future Work

A limitation of this work is the difference in the capabilities of the tools provided for the two conditions. The tablet condition started with a default pen setting that had a similar line thickness (thin) and color (black) to the pen that participants were provided. However, the iPad settings could be easily changed in the tablet condition during the experiment and so participants could (and did) erase, change colors, and change line thickness. On the other hand, the pen condition restricted participants to using a single line thickness and color for the entirety of the session and did not allow them to erase their work. Though this decision was made in order to mirror existing ways in which early stage concept sketching tends to occur using each tool, the differences in features may confound the results in this controlled setting.

Another limitation of this work is that novelty was only assessed based on the primary frothing mechanism. As such, ideas that had creative ways of applying the mechanism or combining multiple mechanisms may have received lower novelty scores despite being relatively creative. Future work could explore other mechanisms of assessing novelty to better capture this aspect. Future work should also explore these metrics for the peanut sheller prompt and determine whether any similarities or differences exist in results between the two prompts. Future work should build on the concept evolution work done here in order to build a metric for quantitatively assessing design evolution patterns.

An additional limitation of the work is that the concept evolution categorization was done by researchers without employing member checking or confirming with participants that they were actually engaging in concept evolution. Future work could use participants' direct input regarding how their ideas were interconnected in order to provide a more comprehensive understanding of concept evolution patterns, especially those that may not be obvious to an outside observer.

This work was conducted in a controlled laboratory setting with students, so future work should explore the role of different sketching tools in the context of real design problems in industry and investigate if there are differences in results between students and practitioners.

Future work could further explore differences in the pattern of consecutive and nonconsecutive design evolution identified here and investigate how this may be linked with other elements of sketches such as quality, novelty, quantity, and even feasibility. There could also be efforts made to quantify this type of design evolution in order to make larger scale comparisons. As this study focused solely on individuals, future work should also assess novelty metrics and concept evolution patterns in teams.

Acknowledgment

Thank you to the participants in the study for their contribution to our work. We would like to extend a special thanks to Morgan Weaver for his advice on novelty assessment methods.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

Appendix: Design Problem—Device to Froth Milk

Problem Description

Frothed milk is a pourable, virtually liquid foam that tastes rich and sweet. It is an ingredient in many coffee beverages, especially espresso-based coffee drinks (Lattes, Cappuccinos, and Mochas). Frothed milk is made by incorporating very small air bubbles

throughout the entire body of the milk through some form of vigorous motion. As such, devices that froth milk can also be used in a number of other applications, such as for whipping cream, blending drinks, emulsifying salad dressing, and many others.

The goal of this project is to design and build *a new innovative product that froths milk in a short amount of time*.

Customer Needs

- Froths milk in a short amount of time
- Minimal instruction needed to use

Please see the reference image below for an example of frothed milk being poured into coffee.

You will have 20 min to brainstorm and sketch *as many ideas as possible*. The goal of this design task is not to produce a final solution to the design problem but to brainstorm ideas that could lead to a new solution. As such, focus on generating as many ideas as possible—*do not focus on the feasibility of your ideas at this stage*.

In your drawings, include enough detail such that someone could understand the main functions of your system. To clearly communicate your concepts, make your drawings large and easy to read with *one idea per sheet* using the template. Number your ideas in the designated location on the template. You can use as many sheets of paper as you like.

For each drawing, please *also write a short caption or idea name of less than a sentence to describe the concept*. You may annotate your sketches to help clarify the components of your designs.

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