Factors Impacting Highly Innovative Designs: Idea Fluency, Timing, and Order

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Ongoing work within the engineering design research community seeks to develop automated design methods and tools that enhance the natural capabilities of designers in developing highly innovative concepts. Central to this vision is the ability to first obtain a deep understanding of the underlying behavior and process dynamics that predict successful performance in early-stage concept generation. The objective of this research is to better understand the predictive factors that lead to improved performance during concept generation. In particular, this work focuses on the impact of idea fluency and timing of early-stage design concepts and their effect on overall measures of ideation session success. To accomplish this, we leverage an existing large-scale dataset containing hundreds of early-stage design concepts; each concept contains detailed ratings regarding its overall feasibility, usefulness, and novelty, as well as when in the ideation session the idea was recorded. Surprisingly, results indicate that there is no effect of idea fluency or timing on the quality of the output when using a holistic evaluation mechanism, such as the innovation measure, instead of a single measure such as novelty. Thus, exceptional concepts can be achieved by all participant segments independent of idea fluency. Furthermore, in early-stage concept generation sessions, highest-rated concepts have an equal probability of occurring early and late in a session. Taken together, these findings can be used to improve performance in ideation by effectively determining when and which types of design interventions future design tools might suggest. [DOI: 10.1115/1.4051683]

Keywords: conceptual design, creativity and concept generation, design theory and methodology

1 Introduction

The purpose of this work is to understand the impact of idea fluency and timing on the output of an ideation session. Ideation is a critical step in the design process [1] that holds the potential for further optimization [2]. With hundreds of design methods available to users [3], there remains a gap between when [4] and which tools to introduce in order to increase a designer's productivity [5]. Tools may increase idea fluency, explore design requirements in more depth, or increase the creativity of ideas. The design research community aims to automate the selection process of which tools to recommend. However, the future development of automated design recommendation systems depends on the detailed understanding of the process dynamics within an ideation session that results in higher performance.

The performance referred to in this study is synonymous with both idea fluency (total number of ideas) and the total output of exceptional ideas (ideas that received the highest possible score from expert evaluators representing approximately 4% of the total dataset). The differentiation between these two performance measures serves to highlight a key topic for exploration of what qualifies a session or designer as "successful." Traditionally, idea fluency is analogous with creativity [6], while highly rated concepts dictate which ideas are worthy of time and resource investment for further development [7]. Early-stage design accounts for an estimated 8% of development costs but determines 70% of the total development cost for a given product [8]. Hence, the optimization of early-stage design can not only result in higher performance designs but also impact a project's budget.

Design metrics provide a means of evaluating a large number of ideas quickly and objectively [9,10]. Idea fluency is straightforward to compute using the numerical quantity of ideas, while design metrics rely on rubrics and human raters to assess each idea. The innovation measure, a multi-attribute-based metric, requires a set of design metric ratings for feasibility, usefulness, and novelty to compute the overall measure [11]. Temporal analyses of design concepts enable researchers to understand when the most innovative ideas occur in an ideation session. The serial order effect, a theory in psychology, describes how one can best recall the first and last items in a sequence [12]. Previous work relating the serial order effect to ideation indicates that more creative concepts occur later in an ideation session [13,14]. However, the exploration of the serial order effect in design has not yet been considered using a holistic design metric, such as the innovation measure.

This research ventures beyond concepts of productivity and sheds light on the innovative bursts and lulls that different types of designers experience. Designers understand that ideation is essential, yet designers of all levels encounter design fixation [15], a measurable barrier in the concept generation process [16–18]. By understanding the process dynamics within an ideation session, not only will this research further the development of automated design tool suggestions but it also advances the knowledge behind when design fixation occurs. The findings on how idea fluency and timing (of idea generation) impact design outputs provide a roadmap for future research directions. Possible directions can explore other interactions within an ideation session, such as design communication [19] or personality traits.

2 Background

2.1 Foundations of Ideation. Early research on brainstorming provides a foundation for success rooted in creative capabilities. Ideation has historically been used interchangeably with

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brainstorming and concept generation. The four rules of brainstorming by Osborn are (1) generate as many ideas as possible, (2) defer judgment, (3) encourage wild ideas, and (4) combine and improve existing ideas [6]. Idea fluency, the number of ideas a person generates, is documented to be synonymous with a person's creativity. Idea fluency is associated with design metrics of novelty or uniqueness of ideas; however, idea fluency alone does not indicate the feasibility or usefulness of an idea. Before Osborn, Guilford's theory of intelligence argues creativity as an innate characteristic of a person [20,21]. The theory describes the operation dimensions of evaluation, convergence, and divergence behavior of a person [22]. According to Guilford, attributes of divergent thinking include characteristics of fluency, flexibility, and originality. Divergent thinking also serves as a metric for idea fluency, Osborn's first rule of brainstorming [6]. Concept generation methods utilized by designers today are based on these foundations. For this research conducted, traditional and alternative evaluation measures of ideation are employed.

2.2 Idea Fluency and Exceptional Ideas. The overall number of ideas, known as idea fluency, is a common theme in the design community often practiced in engineering and design courses [23]. More ideas are seen as a positive characteristic, as prior research has correlated increases in idea fluency with higher creativity [9]. The alternative uses test (AUT), designed by Guilford in 1967, asks participants to generate as many ideas as possible for a simple object—this serves as the foundation of innovation tournaments run by Terwiesch and Ulrich [24]. Terwiesch and Ulrich emphasize an intense and structured approach to innovation requiring high-volume input to detect which opportunities are worthy of pursuing. Based on an empirical study, Kudrowitz and Dippo found that highly novel ideas emerge after nine ideas when using a 3-min alternative uses task [25]. The literature regarding the notion that quantity (idea fluency) produces quality includes work from Diehl and Stroebe that explored individual and group brainstorming structures on idea quality as measured by novelty and feasibility [26]. Paulus et al. evaluated the effect of brainstorming instructions on quality as measured by usefulness [27]. Although researchers consider the impact of idea fluency and the number of good ideas, the measures of "goodness" vary in historical research.

Research in fields outside of design cites that quality is of higher importance than quantity, for example, in economics [28,29] and decision analysis [30]. Furthermore, Jones and Kelly cite that in group discussions, the quality of contributions is paramount to quantity [31]. Therefore, research from other fields might suggest that creating many ideas would result in lower-quality designs compared to one or two well-developed ideas. The counterintuitive approach that holds in design is, although, on average, the quality of ideas may be lower, there should be a few high-quality ideas. Sandnes et al. highlight that more ideas correlate with overall quality [32]. Their study sought to encourage computer science students to focus on quantity rather than fixate on early designs, which ultimately led to spending undue amounts of time and energy on subpar interfaces. Sandnes et al. concluded that students whose goal was to produce as many ideas as possible had higher success rates in achieving the predetermined optimal solution. The researchers point to Monte Carlo [33,34] or stochastic optimization theories [35] as the most logical arguments supporting the notion that *more ideas are better*. In design, the possibility of creative (re)combination has led to a preference towards quantity during early-stage conceptual design—as designers often keep the best features from multiple (early) ideas [36,37].

The current research paper considers whether exceptional idea output is a more valuable measure of success than total idea output. As stated earlier, previous research correlates idea fluency with creativity. Meanwhile, exceptional idea fluency highlights the ideas of interest to further develop based on the highest possible rating for innovation. The latter is worthy of further investigation to determine who generates these exceptional ideas and when.

2.3 Temporal Studies of Design Ideation and the Serial Order Effect. Previous temporal studies in design research include work by Liikkanen et al., who explored the influence of task duration, task decomposition, and time pressure on creativity during ideation [38]. The serial order effect is the tendency for a person to recall the first and last items in a series best and the middle items in a series worst [12]. Applying the theory to concept generation suggests that the best ideas emerge later in the concept generation session. Previous ideation work on serial order focused on when the most creative ideas occurred [13]—where the metrics used referred to uniqueness, novelty, originality, or flexibility [39–43]. Based on those measures of creativity, research from Beaty and Silvia sought to determine the cognitive processes of why more creative ideas emerge late in the ideation process [14]. For the current study, the serial order effect serves as the guiding probe towards identifying patterns in the ideation session concerning the innovation measure—which includes feasibility and usefulness in addition to (only) novelty. The innovation measure is discussed further in the methods (Sec. 3); however, the innovation measure ultimately devalues novel or "creative" ideas that are not realistic as defined by the feasibility or usefulness design metrics. Serial order effect and design ideation remain an open research question in the design research community.

2.4 Interactions of Ideation Factors. Research on creativity and innovation often focuses on the overall ideation session output at a group level. By segmenting sections of the ideation session and by grouping certain designers together based on similar attributes, there is an opportunity for new knowledge of trends, insights, and predictive characteristics that enable designers to be successful. The focus of this work is on the individual level, and therefore no group brainstorming was conducted or examined. Previous work on this topic has focused on extracting design heuristics principles from innovative products [44] and determining "cognitive shortcuts" designers employ to increase productivity [45]. However, the interplay of factors within early-stage concept generation remains unknown.

2.5 Approach. The objective of this work is to understand the impact of idea fluency and timing on the output of an ideation session, as measured by design metrics and exceptional ideas. We propose the following two research questions:

> RQ1: Does generating more ideas increase the probability of generating exceptional ideas?
>
> RQ2: When in an ideation session do the best concepts emerge?

In addressing these questions, the paper first discusses a previous human subject study from which the large-scale data set originates. Then the data cleaning methods and explorative data analyses used for this research are explained. Lastly, the study's results, limitations, and implications are presented, which provide insight into the timing and relevant interventions that may increase a designer's success.

3 Materials and Methods

This study aims to identify the effects that idea fluency and timing have on early-stage concept generation performance. To explore these effects, an existing design research data set from a human subject cognitive study was mined for insights on designer ideation behavior [11]. The previous cognitive study examined varying distances of crowdsourced inspirational stimuli during design concept generation [46].

3.1 Cognitive Study. The cognitive study is described in detail in prior work and summarized here [46,47]. The study involved a 1-h session in which participants developed concept solutions to four different open-ended design problems [16,48–50]. The original experiment contained four conditions. In three conditions, participants received inspirational stimuli (words) that were computationally determined to be varying distances away from the problem domain (near, medium, or far). In the fourth condition, participants received no stimuli (control). The original experiment revealed no statistically significant difference in idea fluency between experimental conditions. The four problems listed in Table 1 were used in a full factorial experimental design (Table 2). Each design challenge lasted 10 min. For each idea generated, participants were responsible for timestamped completion using a clock in front of them. Participants documented their ideas using any form of sketches or words, as shown in Fig. 1.

3.2 Participants. In the cognitive study, a total of 111 participants generated 1652 concepts across the four design problems. For this research paper, data from 66 of the 111 participants data were used. The rationale for excluding participants is discussed further in Sec. 3.4. Participants were upper-level undergraduates and graduate-level students in design and innovation courses at a major US university. They received credit or $10 compensation for their participation. There were 67 male and 44 female participants from ages 19 to 26 ($M = 21.4$). The cognitive study analysis excluded responses from 15 participants used for training the expert raters.

3.3 Research Design. Two expert raters evaluated each concept on four design metrics, based on the rubric below, which were then validated using an intraclass correlation coefficient. The two raters were mechanical engineering graduate students specializing in design methodology and trained extensively on evaluating concepts using the provided metrics and rubrics for this experiment.

(1) **Feasibility**: Rated on an integer scale from 0 (the technology does not exist to create the solution) to 2 (the solution can be implemented in the manner suggested).
(2) **Novelty**: Rated on an integer scale from 0 (the concept is copied from a common and/or pre-existing solution) to 2 (the solution is new and unique). Of note, "novelty" is considered to be the uniqueness of the solution concerning the entire solution set.
(3) **Usefulness**: Rated on an integer scale from 0 (the solution does not address the prompt and/or take into account implicit problem constraints) to 2 (the solution is helpful beyond the status quo).

Table 1 Cognitive study design problems [46]

4. A device that disperses a light coating of a powdered substance over a surface [48]
7. A way to minimize accidents from people walking and texting on a cell phone [49]
11. A device to immobilize a human joint [50]
12. A device to remove the shell from a peanut in areas with no electricity [16]

Table 2 Cognitive study conditions [46]

Problem	Group A ($N = 28$)	Group B ($N = 28$)	Group C ($N = 29$)	Group D ($N = 26$)
4	Medium	Far	Control	Near
7	Far	Control	Near	Medium
11	Near	Medium	Far	Control
12	Control	Near	Medium	Far

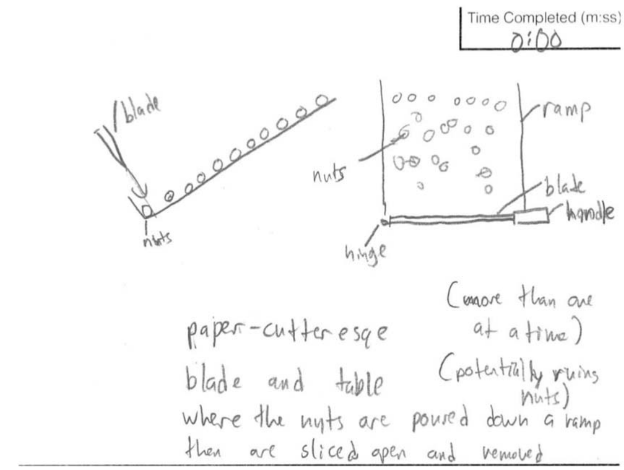

Fig. 1 Example solution from the cognitive study experiment [46]

(4) **Quality**: Rated subjectively by each rater on an integer scale from 0 (low) to 2 (high).

The "design innovation measure" is a new measure developed by Goucher-Lambert et al. that allows for an easy and holistic conceptual design assessment [11]. The formulation of the innovation measure was selected based on correlations between the four design problems' quality metrics. The development of the innovation measure was due to the lack of consensus for the quality design metric, which is traditionally a subjective judgment. The new measure, I, is founded on quantifiable definitions and design attributes that better represent the overall goodness of a design solution, as defined as follows:

$$I = F \times U + N \tag{1}$$

The innovation measure serves as the primary variable for analysis in this study. F stands for feasibility, U for usefulness, and N for the novelty of the design. The innovation measure takes advantage of three out of the four design metric outputs from the cognitive human subject study. The subjective rating of quality validated the nature of the innovation equation. However, the innovation measure omits the quality metric for reasons discussed in Ref. [11], ultimately because of the ambiguity and lack of objective clarity. Moreover, the innovation measure provides a broader range of outputs with whole integers that range from a 0 (low) to 6 (high) scale.

The time documented per idea by the participant is the time remaining in the 10-min ideation session, in minutes and seconds (see the top right corner in Fig. 1). A participant timestamped the completion of their idea after they finished communicating the concept via pen and paper. For the temporal data in this study, the time variable became the time since the start of the concept generation session. The first idea documented began at 2 min and 20 s, while the last idea came at the 10-min mark when time ran out (0:00 value in the cognitive data).

3.4 Data Analysis. A total of 66 participants and 999 ideas remained after removing the incomplete data. This study removed any missing data points for design metrics (feasibility, usefulness, novelty) or idea completion time since they are critical to the analyses performed in the current study. Thus, if a participant was missing at least one data point for their idea, not only was that idea removed but the participant was removed altogether from the analysis.

The innovation measure of a single idea determined the *exceptional idea* classification. Exceptional ideas are any ideas with an innovation score of six, the highest score possible (4% of all

Table 3 Generator classifiers

Idea fluency range		Low (7–13)	Average (14–16)	High (17–26)
All	Ideas (n)	273	266	460
	Participants (N)	24	18	24
Exceptional	Ideas (n)	13	13	11
	Participants (N)	8	7	8

ideas). The key distinction between all and exceptional ideas serves as a direct measure of the success of an ideation session. The differentiation shifts the focus from all ideas to the ideas with the highest probabilities of moving forward in the design process. While the quantity of ideas is analogous with creativity and productivity, exceptional ideas provide a measure for the overall success of a given idea. The sum of exceptional ideas (i.e., exceptional idea fluency) can be used to determine the success of a participant.

Generator and time classifier bins were used in the analysis to better focus on the extremes of high and low-performing individuals, although continuous results and correlations are also presented. *Generator classification* used the total number of ideas generated. The generator classifier distinction statistically described archetypal ideators (e.g., above or below average) based upon the volume of concepts they produced in response to a problem. The number of ideas at the participant level ranged from 7 to 26 ideas ($M = 15.1$) and was divided into three bins of idea generators: low (first third; 0–33%), average (second third; 33–66%), and high (last third; 67–100%). Together, an individual's idea fluency and the total sample mean computed each participant's standard deviation and respective z-score. A z-score to percentile table determined which percentile and bin each idea generator was classified as, as shown in Table 3. To verify that the three idea generator groups were different from one another, a one-way analysis of variance (ANOVA) using average idea fluency rates for each generator bin was determined to be statistically significant ($F(2, 63) = 122$, $p < .001$). Post hoc comparisons using the Tukey honestly significant difference (HSD) test indicated that the generator bin-pairs were also statistically significant ($M_{low} = 11.4$, $SD_{low} = 1.58$), ($M_{avg} = 14.8$, $SD_{avg} = 0.88$), ($M_{high} = 19.2$, $SD_{high} = 2.26$).

The temporal assessment classified each concept as having been generated at the beginning (first third; 0–33%), middle (second third; 33–66%), or end (last third; 67–100%). The time of each concept varied from zero (start of data collection) to 10 min (end of data collection) ($M = 379$ s). The time, in seconds, between the first idea and the last idea for the aggregate population was divided into three equal bins and used to classify each idea as the beginning, middle, or end, displayed in Table 4. Since the time classification uses concepts, note that these ideas are mutually exclusive; however, a participant is not mutually exclusive. Hence, a single participant may have an idea or multiple ideas for each bin. Thus, the summation of participants across all bins exceeds 66 for all ideas and exceptional ideas. The data were normalized to compare across time classifiers, generator classifiers, or time and generator classifiers.

The idea order was determined for each idea. Since each person completed four design problems, they would have up to four first

Table 4 Time classifiers

Time (min)		Beginning (2:21–4:53)	Middle (4:54–7:26)	End (7:27–10:00)
All	Ideas (n)	314	343	342
	Participants (N)	66	66	65
Exceptional	Ideas (n)	13	9	15
	Participants (N)	12	9	12

ideas and four second ideas. The analyses were conducted using all data sets when considering the order and the innovation measure.

4 Results

Using the methods outlined in Sec. 3, the resulting data were analyzed to determine the significance of idea fluency and timing of idea generation on early-stage ideation outputs. First, the overall results presented provide an overview of the total ideation output. Next, idea fluency is explored by looking at all ideas, then exceptional ideas, followed by a visualization of design metrics over the 10-min ideation session. By understanding these interactions within an ideation session, the design research community may more effectively suggest real-time tools that augment a designer's natural talent. Note that lowercase (n) refers to ideas and an uppercase (N) to participants.

For this study, 66 participants generated a total of 999 ideas. Of the 999 total number of ideas, 4% of ideas were classified as exceptional ideas ($n = 37$), generated by 35% of participants ($N = 23$). Figure 2 shows the distribution of ideas by their respective innovation measure. The distribution of ideas by innovation measure is not normal, as tested by the Shapiro Wilk normality test ($W = 0.94$, $p < 0.05$). Figure 3(*a*) shows that the distribution of participants by idea fluency is normal, as tested by the Wilk normality test ($W = 0.98$, $p = 0.36$).

4.1 Impact of Idea Fluency on the Probability to Generate Exceptional Ideas. To determine the impact that the number of ideas has on ideation performance, the entire ideation session was first assessed, followed by an in-depth analysis only considering exceptional ideas. Figure 3(*b*) shows no relationship between the number of ideas generated and the number of exceptional ideas generated by each participant. Due to the definition of exceptional ideas, these ideas must have the highest ratings for feasibility, usefulness, and novelty. The participants with the highest number of exceptional ideas, three, occurred by participants who generated 13, 16, and 18 total ideas. An increase in idea fluency tested with Pearson's correlation coefficient did not correlate with an increase in exceptional idea fluency, $r\ (999) = 0.004$, $p = 0.97$.

The findings demonstrated that all generator segments (low, average, and high) generated exceptional ideas. The number of exceptional ideas and the number of participants who produced exceptional ideas varied across generator groupings. A Chi-square test comparing generator segments and whether exceptional ideas were achieved is not significant, $X^2\ (2, N = 999) = 4.12$, $p = 0.13$). The likelihood of exceptional idea production was 33%, 39%, and 33% for low, average, and high-ideators, respectively. A Chi-square test comparing the number of participants whose ideas

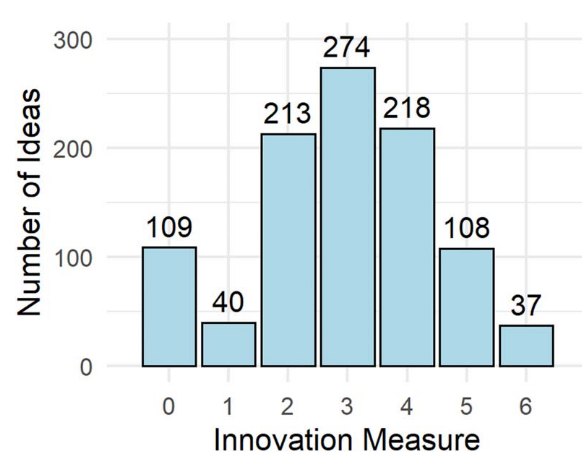

Fig. 2 Idea-level distribution by innovation measure

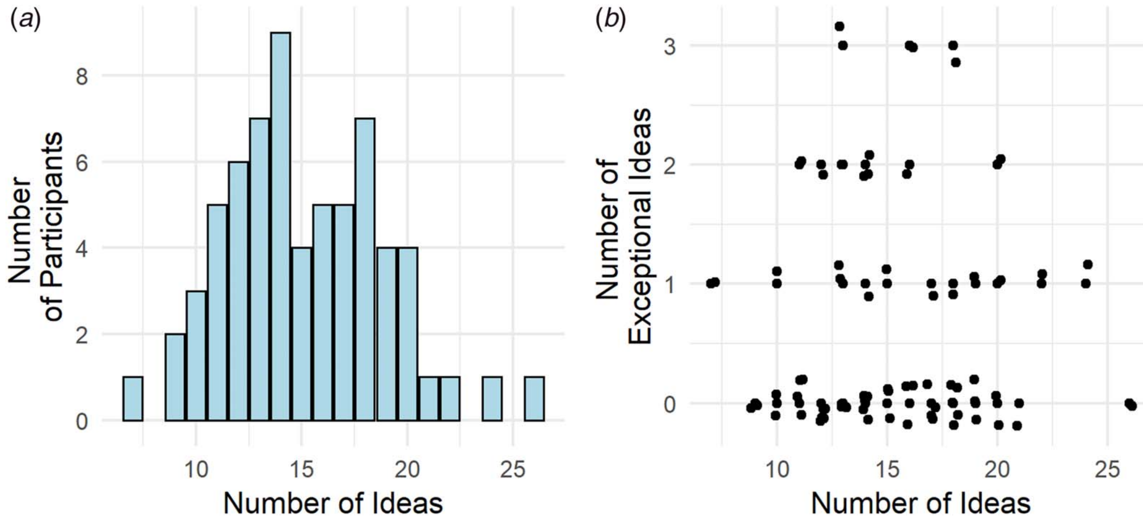

Fig. 3 (*a*) Participant-level distribution by idea fluency and (*b*) relationship between idea fluency and exceptional idea fluency by participant

achieved exceptional ideas and those who did not across the groups is not significant X^2 (2, $N = 66$) = 0.18, $p = 0.91$).

Table 3 shows the number of ideas each segment produced with respect to total and exceptional idea categories, along with the number of participants who generated those ideas. The mean of exceptional ideas produced by a given segment is as follows: low ($M = 1.63$), average ($M = 1.86$), and high ($M = 1.38$). These means are the number of exceptional ideas generated by participants who generated an exceptional idea, not the entire segment population. A one-way ANOVA comparing the segment means is not significant ($F(2,20) = 0.82$, $p = 0.45$). The evidence showed that each segment achieved success regarding exceptional ideas. Thus, to answer the first research question, high-volume idea generators were not more innovative (concerning the mean number of exceptional ideas produced) or more likely to produce exceptional ideas than low idea generators.

4.2 Impact of Idea Generation Timing on Design Metrics and the Probability to Generate Exceptional Ideas. The second research question aims to understand the impact that the serial order effect has on ideas. When in an ideation session do the best concepts emerge? The serial order effect was not observed at either the individual (not shown) or aggregate levels (Fig. 4) with respect to the innovation measure. Figure 4 shows the normalized design metrics used in this study over the duration of the ideation session. The normalization allows for direct comparisons since the innovation measure is on a 0–6 scale while the others are on a 0–2 scale. The rating for innovation has two maximums, at approximately 270 and 500 s, despite having a slight downward trend that is negligible and not statistically significant using Pearson's correlation coefficient, r (999) = −0.027, $p = 0.387$. The two maximums that occur across the design metric curves show the lull that occurred in the middle portion of ideation. Meanwhile, the novelty metric has an upward trend that is expected, r (999) = 0.099, $p = 0.002$. Feasibility and usefulness metrics also experience a small decrease over the 10-min duration, r (999) = −0.120, $p < 0.001$ and r (999) = −0.059, $p = 0.061$, respectively. At the participant level of idea generation, no uniform trends of design metrics were observed concerning time. In this study, 39% of participants experienced an increase in their average innovation, while 61% of participants experienced a decrease in their innovation score over the ideation session. The slope in which a participant's innovation measure increased and decreased varied among participants.

The probability of generating exceptional ideas by time classifier is as follows: beginning (4.14%), middle (2.62%), and end (4.39%). Those percentages were computed using the number of exceptional ideas divided by all ideas, in Table 4, for each time classifier bin. No statistical significance exists across the time classifiers for exceptional ideas for the Chi-square test X^2 (2, $N = 999$) = 1.74, $p = 0.42$). Additionally, 8% of the participants' first idea was their highest-rated ideas; this includes participants who had ideas of the same rating later. First ideas are critical in producing exceptional ideas. They have the highest probability of exceptionality of all ideas at 6.5% of the 263 first ideas generated. As for participants' second ideas, 59% generated higher-rated ideas, 14% generated the same rating, and 27% generated lower-rated ideas, relative to their first idea rating.

Out of the 37 total exceptional ideas, 17 were generated first, nearly half (46%). Meanwhile, the percentage of exceptional ideas for the second-, third-, and fourth-order ideas are 22%, 19%, and 14%, respectively. No exceptional ideas occurred beyond the fourth-order idea for a given participant, although the maximum number of ideas for a design problem was eight.

4.3 Impact of Total and Exceptional Idea Fluency Rates Over the 10-Min Concept Generation Session. In an effort to simultaneously explore both research questions, total and

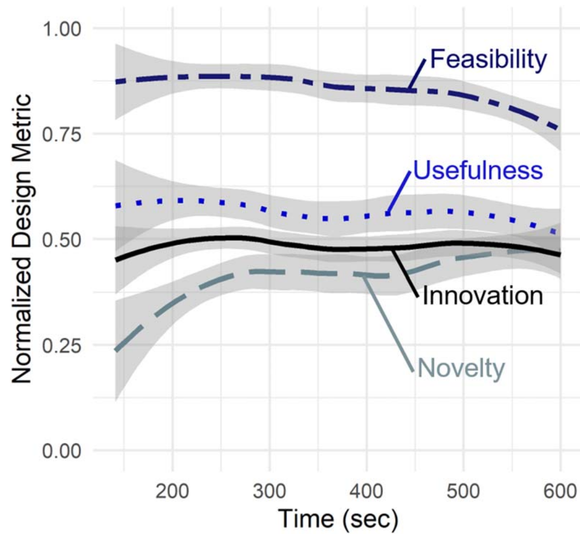

Fig. 4 Normalized design metrics over the 10-min concept generation session

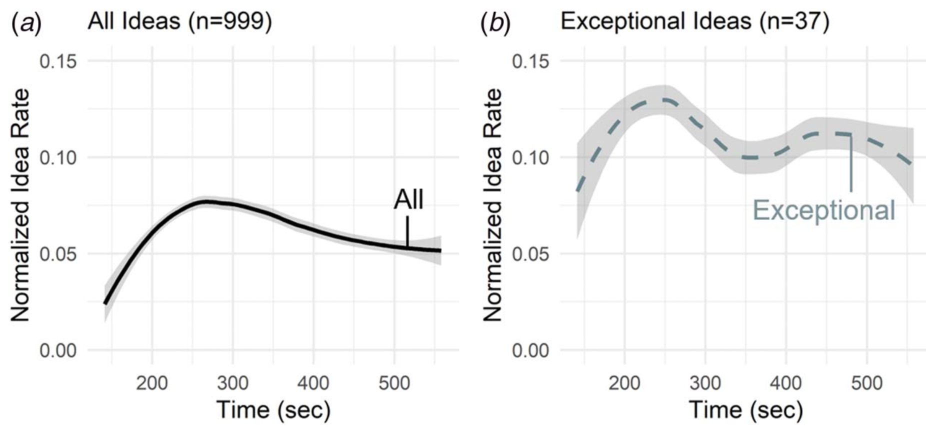

Fig. 5 Idea fluency rates over the 10-min ideation session for (*a*) all 999 ideas and (*b*) 37 exceptional ideas

exceptional idea fluency rates were normalized and plotted as a function of the duration of concept generation. Figures 5(*a*) and 5(*b*) show the normalized idea fluency rates for all ideas (solid line) and exceptional ideas (dashed), respectively. Idea fluency is analogous to productivity at any given moment. At the aggregate level, the graph shows a steady increase as participants begin to ideate and document their ideas, which reaches a local maximum at 270 s. Then the rate slows before it spikes at the final second when time runs out. An analysis of the exceptional ideas, in Fig. 5(*b*), shows two local maxima for exceptional idea generation around 250 and 450 s, respectively, before the curve also spikes at the 600-s mark. Note that this 600-s mark was removed from Fig. 5 since it minimizes the behavior observed before that point. However, three exceptional ideas and 52 non-exceptional ideas occurred in this final moment.

5 Discussion

The objective of this research is to investigate the impact that idea fluency, timing, and order have on concept generation outputs with a focus on the innovation measure. The following sections begin by first discussing the results more broadly and implications for idea fluency, followed by the assessment of timing and order. Additionally, the combinations of idea fluency and time effects are explored along with the limitations of the research project. By understanding the underlying behaviors of early-stage concept generation, the design research community may more effectively automate design tool suggestions that further improve the design process. Note that the term, exceptional ideas, is used when discussing this study's findings which mean ideas that received the highest possible rating on the innovation measure.

5.1 Does Generating More Ideas Increase the Probability of Generating Exceptional Ideas? The study demonstrates no correlation between idea fluency and exceptional ideas (Fig. 3). Therefore, to answer the first research question, generating more ideas does not increase the probability of generating exceptional ideas. The results are surprising in that while we expect more exceptional ideas to come from high-idea generators, no evidence from this empirical study supports this claim.

Designers achieve similar levels of success regardless of the number of ideas they produce. No set number of ideas was necessary to generate exceptional ideas in this concept generation task, as determined by Kudrowitz and Dippo when using the alternative uses task [25]. The success across generator groups is contrary to commonly cited literature in the design research community [6,7,51] that emphasizes the belief that *more ideas are better*. The key difference between previous studies and the current study is the evaluation metric. Prior work utilized the novelty metric and creativity to measure success [23–25]. Work from Kudrowitz and Wallace suggests the use of three separate attributes to screen ideas visually with a spider plot format [9]. In contrast, this study focused on a holistic evaluation criterion—the innovation measure, which combines multiple design metrics into one measure [11]. While this research shows one formulation to quantify innovation (i.e., idea fitness), there are alternative methods to quantify the same concept that may impact future findings. For example, prior work from Miller et al. explored the relationship between two novelty metrics that are widely used and identified a negative relationship resulting in different results where the same concepts were rated differently [52].

We acknowledge that the study herein explores early-stage concept generation, and therefore, current exceptional ideas are generally not the final deliverable. For example, semester design projects usually combine and merge strong concepts, or features of early prototypes, into a final iteration. Existing research showed that combining many traditional components and a rare or new aspect serves as a highly innovative approach to research and technology [36,37,53–55]. Furthermore, Starkey and colleagues found that creativity during ideation does not predict final design creativity [56]. Design fixation and a designer's inability to successfully identify which ideas are highest-rated according to design metrics results in selecting lower-rated ideas [57].

Since these data came from a controlled human subject experiment, there was no constraint of having to build the concept; therefore, the final product for each of the four design problems remains unknown. The impact of the quantity of early-stage concepts on the final design outcome concerning the innovation measure may be an area of future examination for longitudinal studies [58,59]. Moreover, the study participants are design students, which may introduce pressure to generate a high number of ideas for the sake of generating quantity rather than allowing innovation to flow naturally [60].

The distinction between creativity and innovation serves to differentiate the methods designers might use during concept generation. Increasing creativity, novelty, or divergent thinking alone does not lead to increased innovation. Highly novel ideas may not be useful or feasible, resulting in a low innovation measure. Instead, designers should consider alternative methods that increase innovation rather than pursuing the dominant narrative in creativity that quantity leads to quality. Moreover, designers should consider both the goal of an ideation session (e.g., explore design space, cognitive exercise) and its role in the overall design process (e.g., only session versus first of three) when selecting tools or methods for early-stage concept generation. Concept generation is a complex exercise for each person, but how a designer approaches the challenge is individualized.

5.2 When in an Ideation Session Do the Best Concepts Emerge?. The data suggest that as time increases, both the innovation measure (Fig. 4) and the probability of generating exceptional ideas do not increase. Thus, to answer the second research question, exceptional ideas in this study occur at any point in the 10-min concept generation session. No evidence supports the presence of the serial order effect on innovation in early-stage concept generation, which assumes that better ideas emerge late in an ideation session.

Exceptional ideas (defined in this work as ideas with the maximum rating, six, for the innovation measure—Eq. (1)) can be generated at any point in early-stage concept generation. Earlier investigations primarily assess improvement through creativity measures, including variations of the novelty metric that measure each idea's uniqueness relative to others generated [39–43]. The increase in novelty aligns with Guilford's divergent thinking and creativity theories [13,22], which explains the improved novelty formed from unexpected combinations of previous ideas. Moreover, our findings for novelty support research from Beaty and Silvia that tested the serial order effect using novelty and determined that more creative ideas occur later in an ideation session [14]. While the findings align with prior literature that focuses on creativity, perhaps the design research community should consider situations when employing a more holistic approach to quantifying ideation effectiveness would be beneficial. The innovation measure allows for not only the most novel ideas to move forward in concept selection but also the most feasible and useful concepts [11]. Future work from the design research community should continue investigating methods to measure and represent the holistic quality of early-stage design concepts.

Exceptional ideas can occur at any point in any of the four ideation sessions linked to each participant but only occurred within each participant's first four ideas per ideation session. Initial ideas have the highest probability of being rated as exceptional ideas, both among total exceptional ideas ($n = 37$) and total first ideas ($n = 263$). No exceptional ideas occurred beyond the fourth idea. The timing of idea generation represents the point in the zero to ten-min timeframe allotted for the design challenge, while order represents an idea's position relative to other ideas in a session. Exceptional ideas tend to occur within the first few ideas a person generates but those ideas are not necessarily early in an ideation session. For example, designer A and designer B each generate their first ideas, which happen to be exceptional ideas, but designer A's idea occurs at the 3-min mark, which is categorized as early on, while design B's first idea occurs at the end of the ideation session at the 9-min mark. The results indicate that ideas generated fifth in a session and beyond were not exceptional, which also does not support the notion that *more ideas are better* in research question one or that those best ideas emerge late in a concept generation session.

The main takeaway regarding the order of solutions generated during concept generation is that first ideas (those generated first in an ideation session) have the highest probability of achieving an "exceptional" rating. Therefore, regardless of the number of team members and their respective roles, having each person generate at least one but ideally at least four ideas per person would significantly increase the team's innovation potential. Teams cannot rely on the declared designer or creative but rather work together as a collective. These initial ideas are feasible, while later ideas (e.g., ones with a higher likelihood of being novel) can be used to augment earlier ideas. For example, one might borrow an exciting feature from an uncommon and novel late idea to make a first idea even better. The importance of individual brainstorming for exceptional ideas aligns with research from Dunnette et al., which suggests individual brainstorming, followed by group brainstorming, resulted in improved performance [61]. Regardless of the brainstorming methods used (individual or group or both), idea re-combination is a common method that improves outcomes [37,52].

5.3 Do Idea Fluency Rates Improve Over the 10-Min Ideation Session?. In considering exceptional idea fluency over a 10-min concept generation task, Fig. 5 highlights the slow start to ideation that occurs initially, followed by a peak in ideation that occurs at the end. Meanwhile, two maxima were observed for the exceptional idea fluency rate. Concerning the first research question, when total idea fluency is highest, exceptional idea fluency is at a local maximum; however, as total idea fluency decreases, exceptional idea fluency is expected to decrease but instead experiences a second maximum. Moreover, no evidence supports the second research question that best ideas emerge late in concept generation.

The peak resembles the recency effect—a characteristic of the serial order effect. This peak at the 10-min mark represents not only finished ideas but also any unfinished ideas due to time constraints. Meanwhile, no peak of the primacy effect occurs at the beginning of data collection. The lack of a distinguishable primacy peak can be explained by the varying amount of time participants took to read, understand the prompt, and communicate their initial idea. Prior work using neuroimaging to examine the cognitive mechanisms underpinning concept generation identified an initial peak, followed by a sharp decline, for an idea generation period as short as 1-min [62]. Perhaps the delay may represent the time that users need to warm up [63]. Another possible explanation is that sketching ability and expertise impact the communication time and level of detail a designer feels they should include [63,64]. While at a high level, the goal is to create a solution to a design challenge, usually under human-centered design practices, the intermediary goal analyzed is a fraction of the concept on paper in the form of a quick sketch and a brief group of words. Similar studies that utilize sketches have provided participants with upwards of 30-min [65,66].

While a 10-min ideation session sufficed for this study, an extended ideation session may provide further insight into the behavior of idea fluency as a function of concept generation duration. In a 3-h design task where participants were tasked to complete a playground design challenge, participants spent between 6 and 10 min on concept generation activities [67]. Furthermore, future temporal studies in design research may consider using simpler design challenges (e.g., AUT, product names) that reduce the variable that communication time introduces. However, simplified challenges risk moving away from the realities of complex design problems often encountered by designers and engineers.

The observed idea fluency curves (Fig. 5) represent design ideation behavior and can be rationalized considering design logistics; the first ideas are the natural, feasible ideas that generally work. After that initial burst of ideas are documented along with their derivatives, the generation of exceptional ideas slow, which marks the beginning of "wild idea" generation (novel ideas with known low feasibility). At this point, a minimum of exceptional idea fluency occurred. In the process of documenting wild or novel ideas with low feasibility and low usefulness, the second wave of inspiration appeared as the exceptional idea fluency rate increased again. The rise and decrease of idea fluency and design metrics over the 10-min design task can best be related to the four stages of creativity from Wallas [68]. Wallas describes the four stages as preparation, incubation, illumination, and verification. First, users need time to understand the problem, and then they consciously develop their thoughts. Once this process begins, they draw new connections and subconsciously create other ideas in the illumination stage. The verification stage then utilizes more critical thinking to advance their ideas.

While there are some similarities in the observed early-stage ideation herein with the creative process outlined by Wallas, future work on how these stages differ concerning the innovation measure can be of interest. Moreover, Götz and Smith point out that Wallas' theories on the creative fail to account for other factors such as environment [69] or underlying cognitive processes [70,71], which may further impact the innovation measure. The designer's life experience before the cognitive study's design task is unique to each individual. Several external and internal factors may inform a designer's behavior. Regarding the task at hand,

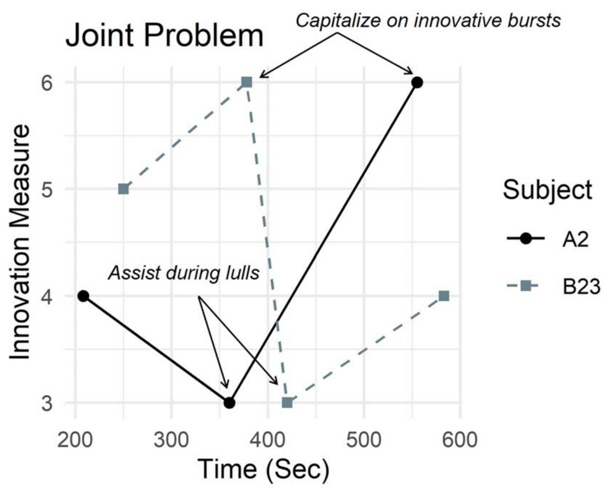

Fig. 6 Design behavior of two participants. The innovation measure and time can be used to determine when to introduce assistance.

designer motivation may also impact design outcomes. One designer might introduce pressure to create the best idea, while another might focus on quantity. Designers might be leveraging the concept generation approach that works for them. This approach might also shift within a session for a problem.

Lastly, the design research community can expand on observations from this work (e.g., Figs. 4 and 5) to more effectively pinpoint when in an ideation session design tools should be recommended. Idea fluency rates or innovation measures for each participant oscillate at various amplitudes and wavelengths over the duration of concept generation/idea order. This potential theoretical framework of design behavior could be possible with a larger sample. The work in this study indicated some trends; however, grouping 66 designers into smaller segments did not allow for significant statistical findings.

Nonetheless, design metrics on the individual level could be visualized and used to determine when automated design tools could be introduced. Figure 6 plots two participants' ideas (with their respective innovation measure scores) throughout concept generation and shows possible moments when design interventions should be introduced. Researchers, educators, and designers alike may seek to improve less productive points in an ideation session—which is when idea fluency rates or innovation measures are low–or instead, they may seek to capitalize on innovative burst—which is when idea fluency rates or innovation measures are high. To quantitatively determine these points of assistance, the first and second derivatives would be utilized. Therefore, enabling more customizable suggestions, which should, in theory, improves a designer's performance in early-stage concept generation. Using a larger subject pool, future work could predict low productivity moments or the point in which designers exhaust their natural concept generation talent [72]. A combination of idea fluency, timing, order, and design metrics could be used in a regression to model performance or productivity.

6 Conclusion

Early-stage concept generation is a critical step in the design process that the design research community seeks to improve, and it needs to be better understood. This study explores the impact of idea fluency and timing on the success of idea generation, as defined by the innovation measure (a holistic measure of overall design quality) and exceptional ideas (approximately 4% of all concepts). The findings show that idea fluency does not correlate with a higher volume of exceptional ideas. Moreover, contrary to popular theories in the design research community, we find that the highest-rated concepts are as likely to occur early as they are late in an ideation session. These findings support the need for the design research community to consider more holistic measures of idea quality when evaluating the success of design ideation periods. The paper provides insight into the process dynamics that make an ideation session productive and a new perspective to analyze concept generation concerning idea fluency and temporal classifiers. The results provide a foundation for future automated design methods and tools which seek to determine when and which type of interventions to suggest in early-stage concept generation.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtained from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper.

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