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THE ROLE OF IDEA FLUENCY AND TIMING ON HIGHLY INNOVATIVE DESIGN CONCEPTS

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ABSTRACT

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 the completion time of each idea. 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 generator 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.

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 (approximately the top 4% highest expert rated concepts). 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 rating each idea requires a set of design metrics to compute the overall innovation measure per idea—a multi-attribute-based metric based on feasibility, usefulness, and novelty [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 creativity may improve over time [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 idea fluency and time provide a roadmap for future research directions that can explore the additional 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 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. 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].

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 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, Kurdowitz and Dippo found that highly novel concepts are likely to occur, after some threshold, in their case after the ninth idea [25]. The literature on the topic that quantity produces quality includes work on the structure of ideation from Diehl and Strebe [26,27]. 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], decision analysis [29], and childcare [30]. Furthermore, Jones and Kelly cite that in group discussions, quality of contributions is paramount to quantity [31]. Therefore, research would suggest that creating many ideas in a ten-minute session would result in lower-rated designs when 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 and colleagues highlight that more ideas correlate with overall quality [32]. Their study sought to encourage computer science students to focus on quantity rather than becoming fixated 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 rates of success 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 ideas consistently improve over time. Previous ideation work on serial order focused on the improvement of creativity over time [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 ideas get more creative over time [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 use of the innovation measure is discussed further in the methods (Section 3); however, ultimately, the innovation measure 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 in the field of 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.

> RQ1: Does generating more ideas increase the probability of generating exceptional ideas?
> RQ2: Do ideas become more innovative over time?

The paper first discusses a previous human subject study, from which the large-scale data set originates from, along with the data cleaning processes and explorative data analyses used for this research. The results, limitations, and implications of the study provide insight into the timing and relevant interventions that may increase a designer’s success.

3. MATERIALS AND METHODS

The purpose of this study is to understand the effects that idea fluency and time have on the performance of early-stage concept generation. 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 the distance 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-hour 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 at 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 minutes. 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 Figure 1.

TABLE 1: DESIGN PROBLEMS ASKED

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

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

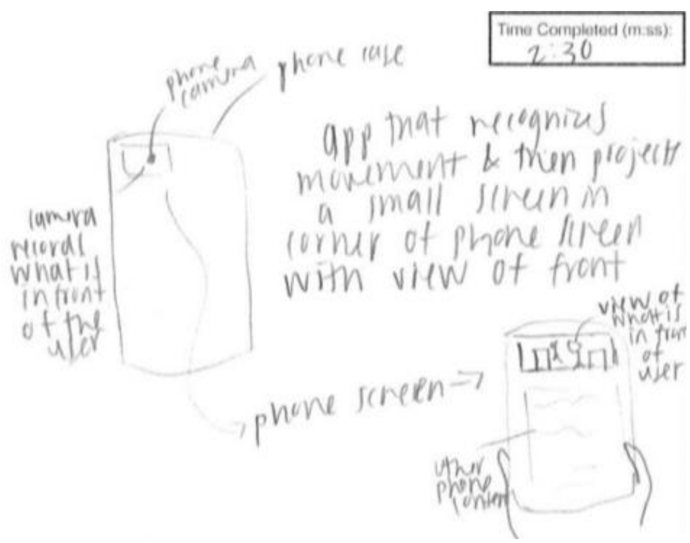

FIGURE 1: EXAMPLE SOLUTION FROM COGNITIVE STUDY EXPERIMENT

3.2 Participants

In the cognitive study, a total of 111 participants generated 1652 concepts across the four design problems. Participants were upper-level undergraduates and graduate-level students in design and innovation courses at a major U.S. 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.

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).
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 that allows for an easy and holistic conceptual design assessment [11]. The development of the innovation measure was due to a lack of consensus for the design metric of quality, 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 below:

$$I = F \times U + N \quad (1).$$

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 [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-minute ideation session, in minutes and seconds (see the top right corner in Figure 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 minutes and 20 seconds, while the last idea came at the 10-minute 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 the data clean-up process. This study removed any missing data points for design metrics or time since they are critical to the analyses performed. 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 a six, the highest score possible (4% of all 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 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 = 15.14), and was divided into three bins of idea generators: low (1st third; 0-33%), average (2nd 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.

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

The temporal assessment classified each concept as having been generated at the beginning (1st third; 0-33%), middle (2nd third; 33-66%), or end (last third; 67-100%). The time of each concept varied from zero (start of data collection) to 10 minutes (end of data collection) (M = 379 sec). The time, in seconds, between the first idea and 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. To compare across time classifiers, generator classifiers, or time and generator classifiers, the data were normalized.

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

4. RESULTS

Using the methods outlined in Section 3, the resulting data were analyzed to determine the significance of idea fluency and time 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 visualization of design metrics over time. The results close by analyzing idea fluency over time by generator segments. By understanding these interactions within an ideation session, the design research community may more effectively suggest tools in real-time 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 classified as exceptional ideas (n=37), which were 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 = 0.93, p < .05). Figure 3A shows the distribution of participants by idea fluency is normal, as tested by the Wilk normality test (W = 0.98, p = .36).

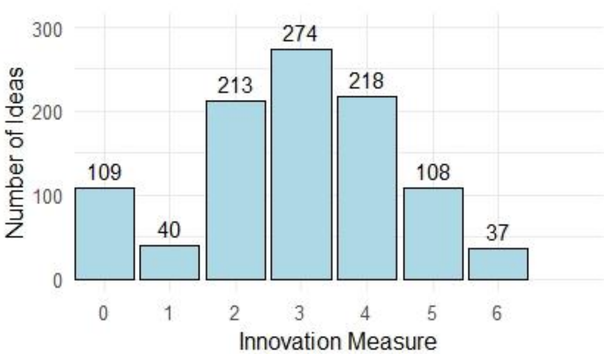

FIGURE 2: DISTRIBUTION OF IDEAS BY INNOVATION MEASURE

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, first, the entire ideation session was assessed, followed by an in-depth analysis only considering exceptional ideas. Figure 3B shows no relationship between the number of ideas generated and the number of exceptional ideas generated by each participant. 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 did not correlate with an increase in exceptional idea fluency.

The findings demonstrated that all generator segments (low, average, 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 the number of exceptional ideas generated per segment is not significant, X^2 (2, N = 999) = 4.12, p = .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 who generated exceptional ideas across the groups is not significant X^2 (2, N = 66) = 0.18, p = .91).

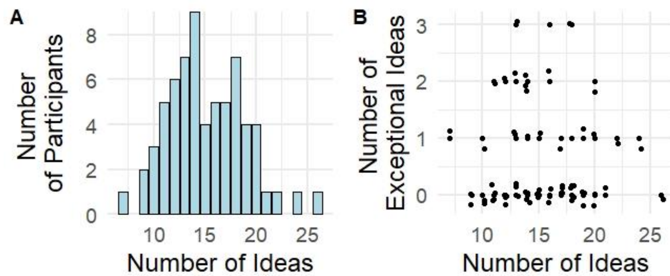

FIGURE 3: DISTRIBUTION OF PARTICIPANTS BY IDEA FLUENCY (A) RELATIONSHIP BETWEEN IDEA FLUENCY AND EXCEPTIONAL IDEA FLUENCY BY PARTICIPANT (B)

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 are as follows: low (M = 1.63), average (M = 1.86), and high (M = 1.38). Note these means are the number of exceptional ideas generated by exceptional participants, not the entire segment population. A one-way ANOVA comparing the segment means is not significant (F(1,21) = 0.47, p = .50). 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 or more likely to produce exceptional ideas than low idea generators.

4.2 Impact of time 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. Do ideas get better over time? The serial order effect was not observed at either the individual (not shown) or aggregate levels (Figure 4) with respect to the innovation measure. Figure 4 shows the normalized design metrics used in this study over time. The normalization allows for direct comparisons since the innovation measure is on a zero to six scale while the others are on zero to two scale. The rating for innovation has two maximums, at approximately 270 and 500 seconds, despite having a slight downward trend. 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.

Feasibility and usefulness metrics also experience a small decrease over time. At the participant-level of idea generation, no uniform trends of design metrics were observed with respect to 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 time. The slope in which a participant's innovation measure increased and decreased varied among participants.

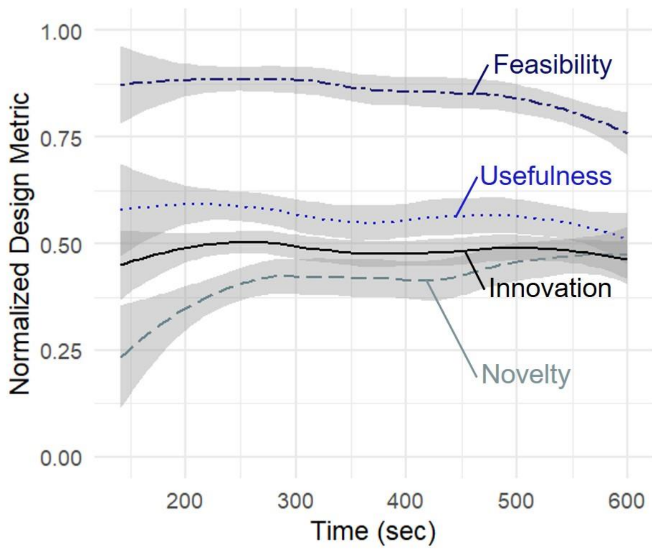

FIGURE 4: NORMALIZED DESIGN METRICS OVER TIME

The probability of generating exceptional ideas by time classifier is as follows: beginning (1.43%), middle (0.48%), and end (1.54%). 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 the Chi-Square test X^2 (2, N = 999) = 1.74, p = .42). Additionally, 8% of the participants' first idea was their highest-rated ideas; this includes participants who had ideas of the same rating later on. However, only 2% of the first ideas generated were exceptional ideas. 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.

4.3 Impact of total and exceptional idea fluency rates over time

In an effort to simultaneously explore both research questions, total and exceptional idea fluency rates were normalized and plotted over time. Figure 5, A and B, show the normalized idea fluency rates for the entire population (solid line) and exceptional ideas (dashed), respectively. Idea fluency over time is analogous with 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 seconds. Then the rate slows before it spikes at the final second when time runs out. An analysis of the exceptional ideas, in Figure 5B, shows two local maxima for exceptional idea generation around 250 and 450 seconds, respectively, before the curve also spikes at the 600-second mark. Note this 600-second mark was removed from Figure 5 since it minimizes the behavior observed before that point. However, three exceptional ideas and 52 non-exceptional ideas occurred in this final moment.

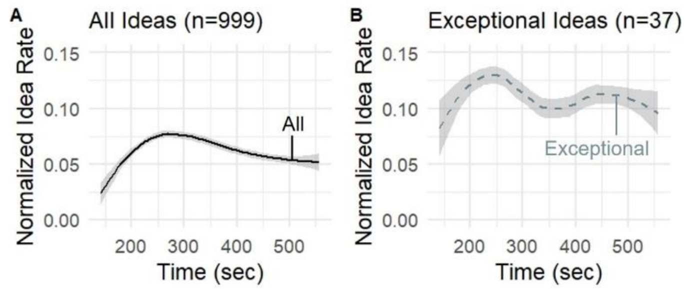

FIGURE 5: IDEA FLUENCY OVER TIME FOR ALL 999 IDEAS (A) AND 37 EXCEPTIONAL IDEAS (B)

5. DISCUSSION

The purpose of this research was to investigate the impact that idea fluency and time 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 time. Additionally, the combination 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 optimize the design process.

5.1 Does generating more ideas increase the probability of generating exceptional ideas?

The study demonstrates no correlation between idea fluency and exceptional ideas (Figure 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 supports this claim.

Designers achieve similar levels of success regardless of the number of ideas they produce. No set number of ideas is needed to generate exceptional ideas. 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 [9,23–25]. In contrast, this study focused on a holistic evaluation criterion—the innovation measure, which is a combination of multiple design metrics [11].

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 [36,37,52–54]. Furthermore, research from Starkey and colleagues found that creativity during ideation does not predict final design creativity [55]. Design fixation and a designer's inability to successfully identify which ideas are highest-rated according to design metrics result in the selection of lower-rated ideas [56].

Since this 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 [57,58]. Moreover, the participants involved in the study are design students, and this may introduce pressure to generate a high number of ideas for the sake of generating quantity rather than allowing innovation to flow naturally [59].

The distinction between creativity and innovation serves to differentiate the methods and tools 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.

5.2 Do ideas become more innovative over time?

The data suggests that as time increases, both the innovation measure (Figure 4) and the probability of generating exceptional ideas do not increase. Thus, to answer the second research question, ideas do not become more innovative over time. No evidence supports the presence of the serial order effect on innovation in early-stage concept generation.

Highly innovative ideas can be generated at any point in early-stage concept generation. Earlier investigations primarily assess improvement through creativity measures, which include 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]. Moreover, our findings for novelty support research from Beaty and Silvia that test the serial order effect using novelty as their metric for improved creativity over time [14]. While the findings align with prior literature that focuses on creativity, perhaps the design research community needs to consider a more holistic approach. 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 to investigate methods to measure and represent the holistic quality of early stage design concepts.

Moreover, observations from this work (Figure 4) suggest that minimums or maximums occur across design metrics. These insights may inform points during concept generation that interventions could be introduced [4], such as the introduction of stimuli or an activity to help increase the desired design metrics. Future work may iteratively predict the chances of generating an exceptional idea for each new idea generated.

5.3 Do idea fluency rates improve over time?

In considering exceptional idea fluency over time, Figure 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 ideas consistently improve over time.

The peak resembles the recency effect—a characteristic of the serial order effect. This peak at the 10-minute 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 take to took 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-minute [60]. Perhaps the delay may represent the time that users need to warm up [61]. Another possible explanation is that sketching ability and expertise both impact the communication time and level of detail a designer feels they should include [61,62]. Similar studies that utilize sketches have provided participants with upwards of 30-minutes [63,64].

While a 10-minute ideation session sufficed for this study, an extended ideation session may provide further insight into the behavior of idea fluency over time. Furthermore, future temporal studies in design research may consider using simpler design challenges (e.g., 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 (Figure 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 highly innovative ideas slows, 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 time can best be related to the four stages of creativity from Graham Wallas [65]. 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 [66] or underlying cognitive processes [67,68], which may further impact the innovation measure.

Lastly, the design research community can use these different rate curves (Figure 5) to more effectively pinpoint when in an ideation session design tools should be recommended. Therefore, enabling more customizable suggestions, which should, in theory, improve a designer's performance in early-stage concept generation. Through the use of a larger subject pool, future work could predict low productivity moments or the point in which designers exhaust their natural concept generation talent [69].

6. CONCLUSION

Early-stage concept generation is a critical step in the design process that the design research community seeks to optimize, 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 the top 4% highest expert rated 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. Concerning the serial order effect, ideas do not become more innovative over time. 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 as well as 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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REFERENCES

[1] Ulrich, K., 1995, *Product Design and Development*, McGraw-Hill.

[2] Zheng, X., Ritter, S. C., and Miller, S. R., 2018, "How Concept Selection Tools Impact the Development of Creative Ideas in Engineering Design Education," J. Mech. Des, **140**(5).

[3] "TDX - Application" [Online]. Available: https://www.thedesignexchange.org/.

[4] Tseng, I., Moss, J., Cagan, J., and Kotovsky, K., 2008, "The Role of Timing and Analogical Similarity in the Stimulation of Idea Generation in Design," Design Studies, **29**(3), pp. 203–221.

[5] Kurtoglu, T., Campbell, M. I., and Linsey, J. S., 2009, "An Experimental Study on the Effects of a Computational Design Tool on Concept Generation," Design Studies, **30**(6), pp. 676–703.

[6] Osborn, A., 1953, *Applied Imagination - Principles and Procedures of Creative Writing*, Scribner, New York, NY, USA.

[7] Reinig, B. A., Briggs, R. O., and Nunamaker, J. F., 2007, "On the Measurement of Ideation Quality," Journal of Management Information Systems, **23**(4), pp. 143–161.

[8] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H., 2007, *Engineering Design: A Systematic Approach*, Springer-Verlag, London.

[9] Kudrowitz, B. M., and Wallace, D., 2013, "Assessing the Quality of Ideas from Prolific, Early-Stage Product Ideation," Journal of Engineering Design, **24**(2), pp. 120–139.

[10] Shah, J. J., Kulkarni, S. V., and Vargas-Hernandez, N., 2000, "Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments," J. Mech. Des, **122**(4), pp. 377–384.

[11] Goucher-Lambert, K., Gyory, J. T., Kotovsky, K., and Cagan, J., "Adaptive Inspirational Design Stimuli: Using Design Output to Computationally Search for Stimuli That Impact Concept Generation," J. Mech. Des, pp. 1–37.

[12] Murdock Jr., B. B., 1962, "The Serial Position Effect of Free Recall," Journal of Experimental Psychology, **64**(5), pp. 482–488.

[13] Christensen, P. R., Guilford, J. P., and Wilson, R. C., 1957, "Relations of Creative Responses to Working Time and Instructions," Journal of Experimental Psychology, **53**(2), pp. 82–88.

[14] Beaty, R. E., and Silvia, P. J., 2012, "Why Do Ideas Get More Creative across Time? An Executive Interpretation of the Serial Order Effect in Divergent Thinking Tasks," Psychology of Aesthetics, Creativity, and the Arts, **6**(4), pp. 309–319.

[15] Jansson, D. G., and Smith, S. M., 1991, "Design Fixation," Design Studies, **12**(1), pp. 3–11.

[16] Linsey, J. S., Tseng, I., Fu, K., Cagan, J., Wood, K. L., and Schunn, C., 2010, "A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty," J. Mech. Des, **132**(4).

[17] Sio, U. N., Kotovsky, K., and Cagan, J., 2015, “Fixation or Inspiration? A Meta-Analytic Review of the Role of Examples on Design Processes,” Design Studies, **39**, pp. 70–99.
[18] Vasconcelos, L. A., and Crilly, N., 2016, “Inspiration and Fixation: Questions, Methods, Findings, and Challenges,” Design Studies, **42**, pp. 1–32.
[19] Häggman, A., Tsai, G., Elsen, C., Honda, T., and Yang, M. C., 2015, “Connections Between the Design Tool, Design Attributes, and User Preferences in Early Stage Design,” J. Mech. Des, **137**(7).
[20] Guilford, J. P., 1950, “Creativity,” Am Psychol, **5**(9), pp. 444–454.
[21] Guilford, J. P., 1967, *The Nature of Human Intelligence*, McGraw-Hill, New York, NY, US.
[22] Guilford, J. P., 1959, “Creativity and Its Cultivation,” Traits of Creativity, pp. 142–161.
[23] Clark, P. M., and Mirels, H. L., 1970, “Fluency as a Pervasive Element in the Measurement of Creativity1,” Journal of Educational Measurement, **7**(2), pp. 83–86.
[24] Terwiesch, C., and Ulrich, K. T., 2009, *Innovation Tournaments: Creating and Selecting Exceptional Opportunities*, Harvard Business Press.
[25] Kudrowitz, B., and Dippo, C., 2013, “Getting to the Novel Ideas: Exploring the Alternative Uses Test of Divergent Thinking,” *25th International Conference on Design Theory and Methodology*, American Society of Mechanical Engineers, p. V005T06A013.
[26] Diehl, M., and Stroebe, W., 1987, “Productivity Loss in Brainstorming Groups: Toward the Solution of a Riddle,” Journal of Personality and Social Psychology, **53**(3), pp. 497–509.
[27] Paulus, P. B., Kohn, N. W., and Arditti, L. E., 2011, “Effects of Quantity and Quality Instructions on Brainstorming,” The Journal of Creative Behavior, **45**(1), pp. 38–46.
[28] Motta, M., 1993, “Endogenous Quality Choice: Price vs. Quantity Competition,” The Journal of Industrial Economics, **41**(2), pp. 113–131.
[29] Keller, K. L., and Staelin, R., 1987, “Effects of Quality and Quantity of Information on Decision Effectiveness,” J Consum Res, **14**(2), pp. 200–213.
[30] Becker, G. S., and Lewis, H. G., 1973, “On the Interaction between the Quantity and Quality of Children,” Journal of Political Economy, **81**(2, Part 2), pp. S279–S288.
[31] Jones, E. E., and Kelly, J. R., 2007, “Contributions to a Group Discussion and Perceptions of Leadership: Does Quantity Always Count More than Quality?,” Group Dynamics: Theory, Research, and Practice, **11**(1), pp. 15–30.
[32] Sandnes, F. E., Eika, E., and Medola, F. O., 2019, “Improving the Usability of Interactive Systems by Incorporating Design Thinking into the Engineering Process: Raising Computer Science Students’ Awareness of Quality versus Quantity in Ideation,” *2019 5th Experiment International Conference (Exp.at’19)*, pp. 172–176.
[33] Halton, J. H., 1970, “A Retrospective and Prospective Survey of the Monte Carlo Method,” SIAM Rev., **12**(1), pp. 1–63.
[34] Liu, J. S., and Chen, R., 1998, “Sequential Monte Carlo Methods for Dynamic Systems,” Journal of the American Statistical Association, **93**(443), pp. 1032–1044.
[35] Bianchi, L., Dorigo, M., Gambardella, L. M., and Gutjahr, W. J., 2009, “A Survey on Metaheuristics for Stochastic Combinatorial Optimization,” Nat Comput, **8**(2), pp. 239–287.
[36] He, Y., Camburn, B., Liu, H., Luo, J., Yang, M., and Wood, K., 2019, “Mining and Representing the Concept Space of Existing Ideas for Directed Ideation,” J. Mech. Des, **141**(12).
[37] Uzzi, B., Mukherjee, S., Stringer, M., and Jones, B., 2013, “Atypical Combinations and Scientific Impact,” Science, **342**(6157), pp. 468–472.
[38] Liikkanen, L. A., Björklund, T. A., Hämäläinen, M. M., and Koskinen, M. P., 2009, “Time Constraints in Design Idea Generation,” *ICED 09, the 17th International Conference on Engineering Design*, Palo Alto, CA, USA.
[39] Johns, G. A., Morse, L. W., and Morse, D. T., 2001, “An Analysis of Early vs. Later Responses on a Divergent Production Task across Three Time Press Conditions,” The Journal of Creative Behavior, **35**(1), pp. 65–72.
[40] Phillips, V. K., and Torrance, E. P., 1977, “Levels of Originality at Earlier and Later Stages of Creativity Test Tasks,” The Journal of Creative Behavior, **11**(2), pp. 147–147.
[41] Parnes, S. J., 1961, “Effects of Extended Effort in Creative Problem Solving,” Journal of Educational Psychology, **52**(3), pp. 117–122.
[42] Runco, M., 1986, “Flexibility and Originality in Children’s Divergent Thinking,” Journal of Psychology - J PSYCHOL, **120**, pp. 345–352.
[43] Ward, W. C., 1969, “Rate and Uniqueness in Children’s Creative Responding,” Child Development, **40**(3), pp. 869–878.
[44] Yilmaz, S., Seifert, C., Daly, S. R., and Gonzalez, R., 2016, “Design Heuristics in Innovative Products,” J. Mech. Des, **138**(7).
[45] Yilmaz, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2016, “Evidence-Based Design Heuristics for Idea Generation,” Design Studies, **46**, pp. 95–124.
[46] Goucher-Lambert, K., and Cagan, J., 2019, “Crowdsourcing Inspiration: Using Crowd Generated Inspirational Stimuli to Support Designer Ideation,” Design Studies, **61**, pp. 1–29.
[47] Goucher-Lambert, K., and Cagan, J., 2017, “Using Crowdsourcing to Provide Analogies for Designer Ideation in a Cognitive Study,” *21st International Conference on Engineering Design (ICED 17)*, Vancouver, Canada, pp. 529–538.

[48] Linsey, J. S., Wood, K. L., and Markman, A. B., 2008, "Modality and Representation in Analogy," AI EDAM, **22**, pp. 85–100.

[49] Miller, S. R., Bailey, B. P., and Kirlik, A., 2014, "Exploring the Utility of Bayesian Truth Serum for Assessing Design Knowledge," Human–Computer Interaction, **29**(5–6), pp. 487–515.

[50] Wilson, J. O., Rosen, D., Nelson, B. A., and Yen, J., 2010, "The Effects of Biological Examples in Idea Generation," DES STUD, **31**(2), pp. 169–186.

[51] Runco, M. A., and Acar, S., 2012, "Divergent Thinking as an Indicator of Creative Potential," Creativity Research Journal, **24**(1), pp. 66–75.

[52] Youn, H., Strumsky, D., Bettencourt, L. M. A., and Lobo, J., 2015, "Invention as a Combinatorial Process: Evidence from US Patents," Journal of The Royal Society Interface, **12**(106), p. 20150272.

[53] Kim, D., Cerigo, D. B., Jeong, H., and Youn, H., 2016, "Technological Novelty Profile and Invention's Future Impact," EPJ Data Sci., **5**(1), pp. 1–15.

[54] He, Y., and Luo, J., 2017, "The Novelty 'Sweet Spot' of Invention," Design Science, **3**.

[55] Starkey, E., Toh, C. A., and Miller, S. R., 2016, "Abandoning Creativity: The Evolution of Creative Ideas in Engineering Design Course Projects," Design Studies, **47**, pp. 47–72.

[56] Mueller, J. S., Melwani, S., and Goncalo, J. A., 2012, "The Bias Against Creativity: Why People Desire but Reject Creative Ideas," Psychol Sci, **23**(1), pp. 13–17.

[57] Shroyer, K., Lovins, T., Turns, J., Cardella, M. E., and Atman, C. J., 2018, "Timescales and Ideaspace: An Examination of Idea Generation in Design Practice," Design Studies, **57**, pp. 9–36.

[58] Hansen, C. A., and Özkil, A. G., 2020, "From Idea to Production: A Retrospective and Longitudinal Case Study of Prototypes and Prototyping Strategies," J. Mech. Des, **142**(3).

[59] Kazakci, A. O., Gillier, T., Piat, G., and Hatchuel, A., 2015, "Brainstorming vs. Creative Design Reasoning: A Theory-Driven Experimental Investigation of Novelty, Feasibility and Value of Ideas," *Design Computing and Cognition '14*, J.S. Gero, and S. Hanna, eds., Springer International Publishing, Cham, pp. 173–188.

[60] Goucher-Lambert, K., Moss, J., and Cagan, J., 2019, "A Neuroimaging Investigation of Design Ideation with and without Inspirational Stimuli—Understanding the Meaning of near and Far Stimuli," Design Studies, **60**, pp. 1–38.

[61] Booth, J. W., Taborda, E. A., Ramani, K., and Reid, T., 2016, "Interventions for Teaching Sketching Skills and Reducing Inhibition for Novice Engineering Designers," Design Studies, **43**, pp. 1–23.

[62] Self, J. A., 2019, "Communication through Design Sketches: Implications for Stakeholder Interpretation during Concept Design," Design Studies, **63**, pp. 1–36.

[63] Daly, S. R., Seifert, C. M., Yilmaz, S., and Gonzalez, R., 2016, "Comparing Ideation Techniques for Beginning Designers," J. Mech. Des, **138**(10).

[64] Vasconcelos, L. A., Cardoso, C. C., Sääksjärvi, M., Chen, C.-C., and Crilly, N., 2017, "Inspiration and Fixation: The Influences of Example Designs and System Properties in Idea Generation," J. Mech. Des, **139**(3).

[65] Wallas, G., 1926, *The Art of Thought*, London, J. Cape.

[66] Götz, I. L., 1981, "On Defining Creativity," The Journal of Aesthetics and Art Criticism, **39**(3), pp. 297–301.

[67] Sadler-Smith, E., 2015, "Wallas' Four-Stage Model of the Creative Process: More Than Meets the Eye?," Creativity Research Journal, **27**(4), pp. 342–352.

[68] Smith, S. M., and Ward, T. B., 2012, "Cognition and the Creation of Ideas," The Oxford Handbook of Thinking and Reasoning.

[69] Gray, C. M., McKilligan, S., Daly, S. R., Seifert, C. M., and Gonzalez, R., 2019, "Using Creative Exhaustion to Foster Idea Generation," Int J Technol Des Educ, **29**(1), pp. 177–195.

