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Does Visual Fixation Affect Idea Fixation?

Divergent thinking, an aspect of creativity, is often studied by measuring performance on the Alternative Uses Test (AUT). There is, however, a gap in creativity research concerning how visual stimuli on the AUT are perceived. Memory and attention researchers have used eye-tracking studies to reveal insights into how people think and how they perceive visual stimuli. Thus, the current work uses eye tracking to study how eye movements are related to creativity. Participants orally listed alternative uses for twelve objects, each visually presented for 2 min in four different views. Using eye tracking, we specifically explored where and for how long participants fixate their eyes at visual presentations of objects during the AUT. Eye movements before and while naming alternative uses were analyzed. Results revealed that naming new instances and categories of alternative uses correlated more strongly with visual fixation toward multiple views than toward single views of objects. Alternative uses in new, previously unnamed categories were also more likely named following increased visual fixation toward blank space. These and other findings reveal the cognitive-thinking styles and eye-movement behaviors associated with naming new ideas. Such findings may be applied to enhance divergent thinking during design.
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1 Introduction

Does staring at a problem make it harder to solve? Where do we look before a moment of insight? Does visually fixating on stimuli for a design problem lead to fixation on presented features? Discovering the eye movements associated with increased creativity may inform effective methods of viewing design stimuli. The results of related eye-tracking research can also be drawn upon to infer the types of thinking reflected in specific eye movements. Thus, new insights may be gained by monitoring eye movements during creativity tasks, e.g., when using visual stimuli in the Alternative Uses Test (AUT) [1]. One eye-movement measure that can be studied is visual fixation, defined as spatially fixated eye movements within 0.5 deg of visual angle.

Our research objective is to discover how visually fixating on pictorially represented objects may affect divergent thinking, as expressed by the ability to derive alternative uses for them. Our research questions, which this paper addresses in detail, are as follows:

(1) What eye-movement behaviors are observed in participants viewing visual stimuli?
(2) Can eye movements reveal cognitive processes underlying divergent thinking?
(3) Can these insights be used to develop methods to enhance divergent thinking?

Motivating these questions and the design of our study are related works, discussed next.

1.1 Divergent Thinking in Design.

This work is motivated by a desire to develop strategies that enhance divergent thinking in design. Divergent thinking is identified as a relevant skill for creativity in design, regardless of the type of design problem [2,3]. Often expressed and measured by the number and variety of different solutions one can derive, divergent thinking represents an ability to explore a design space. Also relevant to engineering design is the role of divergent thinking in developing key engineering-relevant skills such as problem finding, in addition to problem solving [4,5]. The continued exploration of methods to improve divergent thinking, a key facet of creativity, is therefore motivated.

Design researchers (e.g., Olteteanu and Shu; Toh and Miller) have explored how individual differences are related to divergent thinking and have correlated creative performance on a variety of tasks with individual traits [6,7]. The objective of the present work is to instead explore the relationship between eye movements and divergent thinking. Differences between participants and task stimuli are therefore accounted for in the analysis, but not directly compared, as later discussed.

1.1.1 Alternative Uses Test. Guilford's AUT is a creativity test that measures divergent thinking by asking participants to derive alternative uses for common objects [1]. AUT performance is often measured by metrics such as fluency (number of ideas) and flexibility (number of categorically different ideas). The AUT is relevant to design because deriving alternative solutions is a skill required to devise new concepts beyond existing solutions.

This work focuses on AUT performance to gain specific insight into divergent thinking and its related cognitive processes. The AUT was chosen over more extensive design activities that involve decision-making and information-gathering tasks [8]. Beyond invoking divergent-thinking processes, the AUT is a simple task in which idea generation and related behaviors can be observed. The process of idea generation, especially to increase the number of new ideas derived, is essential for creativity in design [9]. By observing AUT performance, the behaviors and cognitive mechanisms supporting idea generation can be found.

1.1.2 Barriers Inhibiting Divergent Thinking. A key to enhancing creativity and novel ideation is the ability to overcome their barriers, including design fixation and functional fixedness. Design fixation, defined as a "blind, and sometimes counterproductive, adherence to a limited set of ideas in the design process" [10],

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is a widely studied phenomenon in engineering design (e.g., [11]). Strategies employing, for example, analogy (e.g., [12,13]), have been demonstrably effective in helping overcome design fixation. Related to both design fixation and the AUT, functional fixedness inhibits the use of an object in a functionally new way due to past experiences with it [14].

Functional fixedness also inhibits divergent thinking on the AUT by limiting the ability to combine diverse information toward creative-idea generation. Beyond its specific effects on identifying alternative uses for objects, functional fixedness is more broadly related to using existing knowledge in different contexts [15,16]. Cropley and Cropley note that the transfer of existing knowledge to different fields is a fundamental part of innovation [17]. Understanding the underlying causes of, and potential methods for overcoming, functional fixedness is therefore important for engineering design.

1.1.3 Idea Fixation. Related to both functional fixedness and design fixation is *idea fixation*, a term we use to refer to participants repeating previously thought-of ideas. In the AUT, functional fixedness can manifest as idea fixation when newly named uses are limited to previously named ways to use or manipulate objects. Repeating old ideas is also an aspect of design fixation, which involves fixating on an existing repertoire of example solutions. Beyond design fixation, or being constrained to *encountered ideas*, idea fixation importantly captures being limited to *one's own devised ideas*.

Idea fixation is used as the main measure of reduced divergent thinking in this study, similar to fixation metrics used by Moreno et al. [18]. To measure fixation, Moreno et al. counted the number of ideas repeated by a participant, which was inversely related to the quantity of ideation. Avoidance of idea fixation, demonstrated by a greater quantity and variety of unique ideas, is thus an indicator of increased creativity [2].

The use of past knowledge may inhibit creativity, as demonstrated by the effects of design fixation and functional fixedness. When assessing the creativity of ideas during the AUT, Benedek et al. excluded as creative those reportedly recalled from long-term memory [19]. However, Yilmaz et al. found that designers may use past experiences as sources for design solutions or building blocks for problem solving [20]. According to Linsey et al., the effective use of analogy in design may also depend on the retrieval of analogies from memory [21]. Accounting for both the inhibiting and encouraging effects of memory on divergent thinking, we approach these competing views on the role of memory in creative thinking by distinguishing new from repeated ideas. Repeating the same potential alternative use for the same or different objects signifies fixation on recently named ideas. As the retrieval of ideas from memory may be important for creative ideation, we do not exclude it, but differentiate processes related to stating new versus previously named ideas. We express this aspect of design fixation and functional fixedness as *idea fixation*, which we use to measure AUT performance. In this study, we observe divergent-thinking ability through the abilities to overcome idea fixation and generate unrepeated ideas in the AUT.

1.2 Divergent Thinking in Cognitive Psychology. While many fields of study are involved in understanding creativity, a cognitive-psychology approach can reveal the thought processes underlying divergent thinking. Neural correlates of divergent thinking can provide insight into how and when creative thought occurs during the AUT. Understanding where the brain is activated and how it behaves during creative tasks informs what can enable creativity from the perspective of memory and cognition.

Different regions of brain activation have been identified while thinking of new and old ideas. Using a functional magnetic resonance imaging (fMRI) study, Benedek et al. found that naming new ideas during the AUT activated the inferior parietal cortex [19]. This brain region is related to directing attention to internal knowledge representations and discriminating between new and familiar information during memory-retrieval tasks. Although an expected difference between thinking of old and new alternative uses might be related to long-term memory retrieval, this was not supported by Benedek et al. Rather than long-term memory retrieval, Madore et al. showed that retrieval of memory related to prior experiences (episodic retrieval) is a key component of creative-idea generation [22]. The use of episodic memory to generate new ideas is seemingly counterintuitive since past experience could appear to worsen rather than enhance the ability to name an object's alternative uses. Madore et al. addressed this apparent contradiction by examining the neural correlates related to both divergent thinking and episodic-memory retrieval [22,23].

The hippocampus is similarly activated during idea generation and during the retrieval and reconstruction of episodic details. According to Romero and Moscovitch, the activation of the left anterior hippocampus during divergent thinking suggests the involvement of event-construction processes [24]. Further supporting a similarity between divergent thinking and event construction, Addis et al. related divergent-thinking ability with the ability to recombine details from autobiographical memories toward detailed simulations of future events [25].

These findings by cognitive-psychology and memory researchers provide a nuanced perspective into the role of memory in divergent thinking, contradicting a possible misconception that memory retrieval during the AUT increases fixation to old ideas. Long-term memory should not necessarily be suppressed to enable new ideation but should be searched for relevant information as the process of combining known details from memory can enhance divergent thinking. As discussed below, insights from cognitive psychology also inform the current work on how visual stimuli are perceived, and what eye movements may reveal about cognition.

1.3 Visual Representations of Objects During the Alternative Uses Test. When administering an AUT, the choice of stimulus to visually represent an object is neither obvious nor arbitrary. Flowers and Garbin suggest that high AUT performance is associated with the ability to perceptually represent a given stimulus in multiple ways [26]. Counterintuitively, displaying a single view of an object may encourage the activation of processes related to this perceptual ability, whereas showing multiple views may reduce such activation. In contrast, McCaffrey and Krishnamurty identify the value of revealing obscure features of objects to overcome functional fixedness [27]. Providing multiple views may facilitate greater consideration of an object's features, when compared with presenting a single view of the object. Conventionally, engineering drawings often show objects in multiple views (i.e., three orthogonal and one isometric).

The use of multiple views is supported by an fMRI study by Chrysikou and Thompson-Schill [28]. In their study, brain activity during common- versus alternative-use identification revealed the importance of object representation. Alternative-use identification is related specifically to increased attention to visual aspects of the object, which enables useful associations with features such as size and shape. These features might be suppressed and irrelevant during common-use identification. Actively attending to different visual aspects of an object, not obviously related to its common use, may therefore improve AUT performance. Contrarily, Chrysikou et al. suggest that when deriving alternative uses, pictorial stimuli may be altogether less effective than verbal stimuli [29]. During the AUT, pictures, compared to words alone, led to more responses related to the object's normal use. Pictures may provide information about actions normally associated with the object, while words may support broader associations with the object.

Creativity tasks such as the AUT can be performed without pictorial stimuli, but engineering-design activities may require or recommend the use of such stimuli. Toh and Miller encourage the visual inspection of two-dimensional pictorial representations of products in the initial stages of design [30]. Lauff et al. observed that benchmarking and reverse engineering of existing designs is a common practice in the early stages of product design [31].

Monitoring eye movements during an AUT may clarify the specific mechanisms of processing visual stimuli that lead to unique, previously unnamed ideas. In the present study, AUT objects are shown in four different views, and eye movements are monitored to explore the role of multiple views in generating new ideas.

1.4 Eye Movements Related to Design, Cognition, and Creativity. Discussed below are eye-tracking studies reported in the design literature and related to cognition and creativity. These have motivated the use of eye tracking in the current work.

1.4.1 Eye-Tracking Studies in Design. Design researchers have employed eye-tracking tools in various ways, including in design fixation. Starkey et al. studied eye movements during product dissection in the context of an engineering-design task [32]. They hypothesized that increased average visual-fixation duration on visible parts during product dissection would predict part reuse in design. Their findings did not support that increased visual fixations were related to unconscious design fixation on observed parts. Smith et al. used eye tracking to determine whether eye movements on example poster designs would predict design fixation. Reuse of elements from the example design was not predicted by where participants first looked, nor by the longest or most frequent eye movements [33]. These studies do not provide evidence that eye movements reveal unintentional design fixation.

MacDonald et al. have employed eye tracking in product-design research toward understanding user preferences of product features. They found that a feature's importance correlated with increased eye movements on that feature [34,35]. Related to our work, looking at an object's features during the AUT may reveal a preference for specific features and a corresponding effect on alternative-use generation.

Eye-tracking research in design has been mostly limited to measuring where designers look during a design task. One aim of the present work, rather, is to observe whether eye-movement behaviors can reveal the cognitive processes associated with divergent thinking and whether they are helpful for AUT performance.

1.4.2 Eye-Tracking Studies in Cognition and Creativity. Beyond providing insight into how visual stimuli are used, eye movements can reflect different types of thinking. Observing eye movements related to idea fixation is useful not only as a measure of unintentional bias toward visual features but also to reveal how a participant is thinking in real time.

A variety of eye-movement measures have been studied during the thinking processes involved in creativity. Benedek et al. observed eye movements during internally directed cognition (IDC) [36]. IDC supports the formation of novel mental representations, which is useful while planning or generating creative ideas [37]. During IDC, visual disengagement from external stimuli and reduced visual fixations were observed. Ueda et al. explored the relationship between AUT performance and blinking [38]. The activation of divergent-thinking processes when naming alternative uses correlated with increased eye-blink rates. Salvi and Bowden further linked improved creativity to looking-at-nothing and increased blinking, both of which are associated with looking away from the external visual environment [39].

The present study similarly uses eye tracking to investigate the relationship between divergent thinking and eye movements. Specifically, we observe whether eye-movement behaviors during the AUT can predict instances of overcoming idea fixation or the tendency to name new versus repeated ideas. By observing how visual fixation may affect idea fixation, we can gain insight into the relationship between eye movements and divergent thinking.

2 Materials and Methods

The current work uses eye tracking to identify eye movements related to idea fixation when participants derived alternative uses for 12 different objects. While participants were shown each object on a computer screen for two minutes, their oral responses for alternative uses were recorded. At the same time, their eye movements on the screen were also recorded using eye-tracking equipment. Visual fixation observed during the task was then correlated with AUT performance, providing insight into how participants viewed visual stimuli during idea fixation versus divergent thinking. Eye movements and oral responses were analyzed for each two-minute AUT completed by each participant ($n = 15$ participants $\times$ 12 objects $= 180$) and for each alternative use named ($n = 1141$).

2.1 Eye-Tracking Study Design. The procedure, visual stimuli, and equipment used to conduct this eye-tracking study are described next.

2.1.1 Participants. Participants consisted of 15 healthy adults (9 female + 6 male; mean age, 25.5 years; SD, 5.7 years) recruited through the adult participant pool at the Rotman Research Institute at Baycrest Hospital in Toronto. Participants provided informed consent before taking part in the study and received \$10/h of compensation. One participant, not included in the above 15, was excluded from analysis due to having eye-movement measures >2 standard deviations away from the group mean. In the current paper, data from the remaining 15 participants were analyzed.

Feasibility and cost constraints have limited our recruitment of more participants; however, studies using similar eye-tracking or neuroimaging techniques recruit a comparable, if not smaller, number of participants [32,40,41]. The results of our observational study provide promising avenues for future work, without asserting the effectiveness of any particular design intervention. Given the exploratory nature of our work, a priori power analyses were not conducted. However, the possible effects on our results due to the small sample size used are discussed.

2.1.2 Alternative Uses Test Instructions and Visual Stimuli. Each participant completed the AUT for 12 objects, during which they named out loud alternative uses for each object for two minutes while their eye movements were measured. They were asked specifically to generate as many different uses as possible, different from their normal use and different in kind from each other. At the start of the study, participants were told they had two minutes for each object.

AUT objects ranged in size and included: (small) key, paper clip, push pin; (medium) mug, brick, pencil, hanger, screwdriver; and (large) table, chair, barrel, tire. These objects were chosen as they were used in previous studies involving the AUT (e.g., [29,42,43]). For each object, instructions, e.g., "Please name alternative uses for a paperclip, as shown in the next display" were shown for five seconds, followed by the image of the object, shown for two minutes, during which participants provided oral responses. After each object, a cross appeared on screen to ensure drift correction of the eye-tracking equipment. The presentation order of objects was randomized for each participant.

Participants were shown each object presented in four different views on a single screen: three orthogonal views (top, front, and right) and one isometric view (from the corner intersecting top, front, and right views). Before the start of the study, a sample image of an abstract object (not used in the AUT) presented in these views was shown, allowing participants to anticipate and understand subsequent images. Figure 1 shows sample stimuli displayed to participants for a paperclip. Appendix A shows visual stimuli provided for all objects. Each image was 814×654 pixels in size and displayed to participants centered on a 1024×868 resolution, 19-in. computer screen.

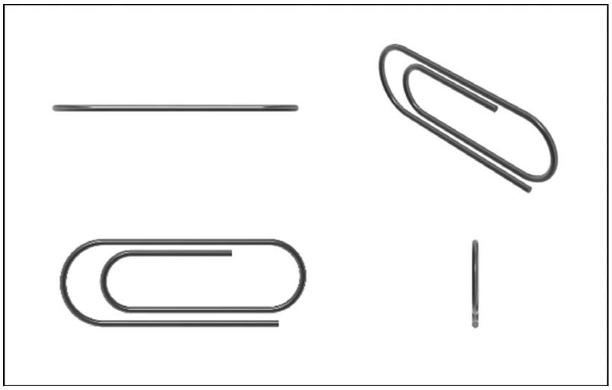


Fig. 1 Example visual stimuli for paperclip shown in the AUT

Table 1 shows the isometric views of all twelve objects. Images of each object view were obtained from four specific orientations of computer-aided design figures. Selecting specific orientations increased the consistency of how different objects were presented, to help participants understand and be able to anticipate what would be shown. For each object, the ratio of the pixel area occupied by all four object views divided by total pixel area of the screen is also provided. The proportion of blank space on the screen is correspondingly determined. Also shown in Table 1 are the range of values for weighted object fixation and weighted blank fixation, defined later in Sec. 2.2.2.

2.1.3 Apparatus. Stimuli were presented on a 1024×768 resolution, 19-in. Dell M991 monitor. Eye movements were recorded from one eye (selected as described next) using a head-mounted EyeLink II eye-tracking system at 500 Hz sampling rate with 0.5 deg accuracy (SR Research Ltd., Mississauga, Canada). Prior to the study, a nine-point eye-movement calibration was conducted for each participant. Accuracy during the calibration process determined which eye was recorded for the study. Before each object, a drift correction (5 deg) was performed, accounting for head and body movements occurring between objects. The need for recalibration of equipment was noted during the study, and its effect on eye movements on the previous object examined post hoc. For each object, post hoc inspection for calibration errors was also done to ensure that measured fixations were not far removed or shifted away from relevant stimuli.

2.2 Alternative Uses Test Study Design. This section describes the structure of our AUT study, and how alternative uses and eye-movement measures were evaluated. Our analysis was conducted at two distinct levels. The first is at the trial level, where a trial is a complete two-minute AUT for one object by one participant. The second is at the event level, where two events are associated with each named alternative use (AU): a response event and a silent event. A response event covers the time during which an AU is named and described aloud. A silent event precedes each response event and is associated with the time between responses when nothing is spoken aloud by the participant. Benedek et al. followed a similar experimental design, separating silent idea generation from vocalization of responses [19]. Karson et al., in an early study on task differences in blink rates, found that speaking tasks, different from non-speaking tasks, are correlated with increased blinking rates [44]. Since increased blinking is also related to increased creativity [38,39], thinking and speaking events are separated in the analysis to account for their differences in eye movements.

Figure 2 visually depicts the nested relationship between participants, AUT trials, and events. Each participant completed an AUT for 12 objects, resulting in a total across all participants of $T = 180$ trials (15 participants $\times$ 12 objects). Within each trial, a participant named aloud i alternative uses, resulting in $\sum_1^T i$ events across all T trials. In this study, 1141 alternative uses were named; thus, 1141 silent events and 1141 response events were included in the analysis. Events are further described in the next section.

2.2.1 Timing of Events During the Alternative Uses Test. Participants provided oral responses, which were audio-recorded. Over a two-minute trial, timestamps were labeled for the start and end of each recorded response to identify each silent event and response event. IBM Watson's speech-to-text software, which transcribes audio files with timestamps for each spoken word, was used to partially automate this process. When words were missing from the transcription, this was supplemented by manually transcribing responses and identifying start and end times to the nearest 0.5 s (rounded up for end times and rounded down for start times).

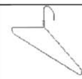
2.2.2 Measures of Visual Fixation. The measures related to visual fixation (VF), defined in the nomenclature as "spatially fixated eye movements (within 0.5 deg visual angle)," are summarized in Table 2. These measures are divided into general and location-based measures. Under general measures, *VF count* and *VF average duration* are the number and average duration of visual fixations, respectively, for a given trial or event. *VF proportion* refers to total VF duration relative to total trial or event duration.

To evaluate the effect of looking at versus away from the object, visual fixations on and off the object were separately labeled. For each view of the object, a 10-pixel-wide perimeter was traced around the object. Collectively, the total VF duration within these regions is *Object VF*, and the total VF duration outside these regions is *Blank VF*. Normalizing Object VF with respect to time and area, *Weighted object fixation* is the ratio: (Object VF/total VF duration)/(% object area on the screen) as shown in Table 1. *Weighted blank fixation* similarly defines relative time spent visually fixating toward blank space on the screen. For example, for the object "brick," if 60% of visual fixation is on the object and 40% on blank space, weighted object fixation is $0.6/0.23 = 2.61$ and weighted blank fixation is $0.4/0.77 = 0.52$. Every trial and event was also assigned an *object-focus type*: *none, single-focused,* or *multi-focused.* Single-focused trials and events are those where >50% of Object VF is toward one of four views, whereas, for multi-focused, ≤50% of Object VF is on a single view. When there was no visual fixation on the object (in events only), an object-focus type of *none* was assigned.

2.2.3 Measures for Alternative Uses Test Responses. The metrics used to assess alternative uses are summarized in Table 3. For each participant, alternative uses were analyzed in the order in which they were named, i.e., for alternative uses 1 to i in trials 1–12. A category including each alternative use was identified, e.g., using a paperclip as a ring is categorized as jewelry. Jewelry is a category that also includes earrings or pendants. In sequence, each alternative use was identified as being new (1) or repeated (0) by the current participant in the current or previous trials as a binary score of *idea newness*. A repeated idea involves the exact or only slight variation or rewording of a previously stated idea, consistent with Moreno et al. [18]. *Category newness* was similarly assessed based on whether the category was new (1) or had been repeated (0) by the current participant. In subsequent event-based analyses, idea and category newness scores of each AU were related to visual fixation during associated silent and response events. Excluded from analysis are responses describing the common use of the object (e.g., a paperclip to hold paper together), and not its possible alternative use. To illustrate, Appendix B contains the full list of categories and examples of new versus repeated alternative uses belonging to each category given by Participant #3.

Once categorized, the total number of ideas and categories, unrepeated from the current or previous trials, were counted for each trial as measures of fluency and flexibility, respectively. Fluency is the sum of idea newness scores, and flexibility the sum of

Table 1 Characteristics of 12 objects used in the AUT

Object Name	Isometric view	**% Object area (on screen)** [Range of weighted object fixation*: 0 to 1/(%object area)]	**% Blank area (on screen)** [Range of weighted blank fixation*: 0 to 1/(%blank area)]
Barrel		**21** [0 to $\frac{1}{0.21} = 4.76$]	**79** [0 to $\frac{1}{0.79} = 1.27$]
Brick		**23** [0 to 4.35]	**77** [0 to 1.30]
Chair		**12** [0 to 8.33]	**88** [0 to 1.14]
Hanger		**12** [0 to 8.33]	**88** [0 to 1.14]
Key		**10** [0 to 10]	**90** [0 to 1.11]
Mug		**24** [0 to 4.17]	**76** [0 to 1.32]
Paper clip		**16** [0 to 6.25]	**84** [0 to 1.19]
Pencil		**7** [0 to 14.29]	**93** [0 to 1.08]
Push pin		**19** [0 to 5.26]	**81** [0 to 1.23]
Screwdriver		**9** [0 to 11.11]	**91** [0 to 1.10]
Table		**14** [0 to 7.14]	**86** [0 to 1.16]
Tire		**24** [0 to 4.17]	**76** [0 to 1.32]

*Weighted blank fixation and weighted object fixation are defined in Sec. 2.2.2.

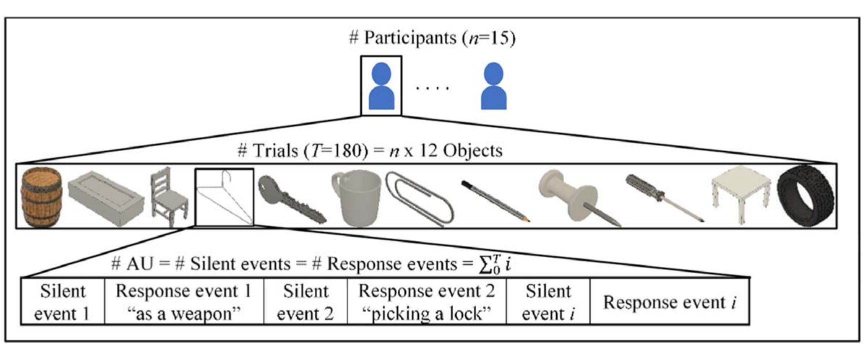


Fig. 2 Relationship between participants, trials, and events in AUT study

category newness scores for all AU's in a trial. Fluency and flexibility are related to Shah et al.'s measures of ideation effectiveness: quantity and variety, respectively [45]. Others have expanded upon initial measures of creativity and idea effectiveness to evaluate engineering designs with e.g., novelty [46], simplicity [47], or quality [48]. However, the use of these more complex engineering-design metrics is limited when evaluating the simple AUT responses obtained in this study.

To address the potential bias introduced when labeling concepts into mutually exclusive categories, inter-rater reliability between

Table 2 Measures related to VF

1. General measures for VF	
VF count	# of VF in a trial or event
VF average duration	Average VF duration in a trial or event (ms)
VF proportion	Proportion of total VF duration relative to trial or event duration
2. Location-based VF	
Object VF	VF duration on object (ms)
Blank VF	VF duration away from object, on blank portions of screen (ms)
Weighted object fixation	$\frac{\text{Object VF/total VF duration}}{\text{\% object area on screen}}$
Weighted blank fixation	$\frac{\text{Blank VF/total VF duration}}{\text{\% blank area on screen}}$
Object-focus type	*Single-focused*: >50% Object VF is on one object view *Multi-focused*: ≤50% Object VF is on one object view

Table 3 Metrics for AUT responses

1. Event-based analysis for each alternative use	
Idea newness (binary score)	**1** for new AU, **0** for AU repeated from current or previous trial by current participant
Category newness (binary score)	**1** for AU that belongs to a new category, **0** for AU from category repeated from current or previous trials by current participant
2. Trial-based analysis (each AUT)	
Fluency	Sum of # AUs in a trial, unrepeated from current or previous trials by current participant
Flexibility	Sum of # AU categories in a trial, unrepeated from current or previous trials by current participant

two independent raters was performed for scoring idea and category newness. Cohen's Kappa, used to determine inter-rater reliability between two independent raters, was found to be 0.85 and 0.81 for category and idea newness, respectively, corresponding to an almost perfect agreement [49]. Differences in ratings were discussed between raters and reconciled accordingly prior to analysis.

In our discussion on idea fixation, we refer to:

(1) Alternative uses that are repeated or belong to a category previously stated by the current participant, i.e., no new idea or category of idea is derived by the participant during the associated event.
(2) Lower counts of new ideas or categories of ideas over a trial, as measured by idea fluency and flexibility scores.

3 Results

The below analysis examines the relationship between eye movements and AUT performance. Specifically observed is how visual fixation is related to idea fixation, in both trial-based and event-based analyses. The trial-based analysis (at the participant-object level) explores the relationship between visual fixation during a trial and associated fluency and flexibility scores. In the event-based analysis (silent or response), the differences in visual fixation when naming new versus repeated ideas, or categories of ideas, are considered. Also addressed in event-based analysis are differences in eye movements in speaking (response) and non-speaking (silent) events.

At the trial (participant-object) level, differences in eye movements between high and low fluency and flexibility scores are expected. In silent and response events, differences in eye movements related to naming new and repeated ideas are expected. As previously discussed, we hypothesize that eye movements involved in creative cognition including, e.g., gaze aversion from external stimuli [36,38,39], will correlate with reduced idea fixation.

3.1 Trial-Based (Participant-Object) Analyses. Corresponding to trials completed by all participants, Fig. 3 shows a histogram of fluency and Fig. 4 shows a histogram of flexibility. Each bar represents the percentage of trials with the number of new ideas

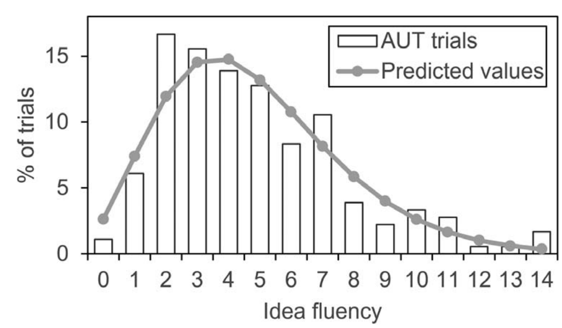


Fig. 3 Histogram of idea fluency in a trial (as % of trials with specified idea fluency), and predicted probabilities derived from negative binomial regression model ($n = 180$)

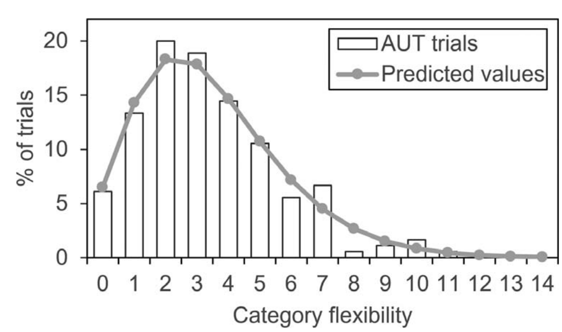


Fig. 4 Histogram of category flexibility in a trial (as % of trials with specified category flexibility), and predicted probabilities derived from negative binomial regression model ($n = 180$)

(Fig. 3) or AU categories (Fig. 4) specified in the x-axes. Negative binomial regression models, used to model non-normal count data, were built to predict the total count of new ideas (fluency) and new categories of ideas (flexibility) of a trial based on measures of visual fixation. Generalized estimating equations were used for estimation

Table 4 Descriptive metrics of trial-based analysis

Descriptive metrics of trial-based analysis ($n = 180$)		
VF measure	Median (min, max value)	Standard deviation
VF count	317 (166, 538)	82
VF average duration (ms)	314 (184, 640)	95
VF proportion (of trial duration)	0.86 (0.60, 0.93)	0.06
Weighted blank fixation	0.74 (0.03, 1.2)	0.30
Weighted object fixation	2.6 (0.16, 8.9)	1.6
Idea fluency	4 (0, 14)	2.9
Category flexibility	3 (0, 14)	2.5

Table 5 Negative binomial regression model predictors of idea fluency ($n = 180$)

VF measure	β(Standard error)	Exp(β)	p
Significant predictors of idea fluency by trial			
Object-focus type[a]	0.91(0.36)	2.5	<0.01
Interaction effects			
Object-focus type[a] and VF average duration (ms)	−0.0024(0.0018)	0.99	<0.01

[a]Comparing multi versus single object focus.

due to the presence of repeated measures in these models. Repeated measures were used to account for differences between participants and objects. Overlaying the frequency distributions in Figs. 3 and 4 are the predicted values of fluency and flexibility derived from the negative binomial regression models. Descriptive metrics of visual fixation by trial are summarized in Table 4.

3.1.1 Idea Fluency. Table 5 lists the significant effects (object-focus type and the interaction effect between object-focus type and VF average duration) observed between idea fluency and visual fixation. Reported in Table 5 are the β coefficients of the significant predictors of the regression model. Insignificant effects (VF count, VF average duration, VF proportion, weighted object fixation, and weighted blank fixation) are not shown. Visually fixating on one instead of multiple object views was associated with decreased idea fluency ($\beta = 0.91$ and $p < 0.01$). Examples of visual-fixation patterns related to single and multi-focused trials, corresponding to low and high fluency scores respectively, are shown in Fig. 5.

There was also a significant interaction effect between object-focus type and VF average duration ($\beta = -0.0024$ and $p < 0.01$), shown in Fig. 6. Visual fixation toward multiple versus single object views correlated, on average, with higher fluency. This effect was moderated by the duration of eye movements toward multiple views, such that shorter visual fixations toward multiple views are more related to increased idea fluency. A possible interpretation of this is that the most effective use of multiple stimuli is related to shorter visual fixations and increased sampling of multiple views. From these results, we infer that attending to multiple views of the object may be helpful for improved divergent thinking.

3.1.2 Category Flexibility. The same relationships observed between visual fixation and idea fluency were found for category flexibility, as summarized in Table 6, showing the β coefficients of the significant predictors of the regression model. Category flexibility was significantly related to object-focus type. When participants viewed more than one object view for >50% of the time, higher category flexibility was observed ($\beta = 1.3$ and $p < 0.001$).

Figure 7 shows examples of single-focused trials versus multi-focused trials related to low and high flexibility scores, respectively. The interaction effect between object-focus type and VF average duration was also a significant predictor of category flexibility ($\beta = -0.0035$ and $p < 0.001$). Figure 8 shows the interaction effect between object-focus type and VF average duration for category flexibility (versus idea fluency shown in Fig. 6). The similarity between these and idea fluency results is expected since flexibility and fluency scores are highly correlated ($r = 0.88$ and $p < 0.001$). All other variables were insignificantly related.

3.1.3 Effect of Object Representation on Object-Focus Type. Looking at multiple views of the object was associated with both increased idea fluency and category flexibility, as discussed above. However, it is possible that the visual representation of objects affected the tendency to view them in single versus multiple views. The effect of object features such as the number of unique views, size of objects, and material uniformity on object-focus type is next explored.

To keep the visual representation of objects consistent, they were, as mentioned, shown in three orthogonal views and one isometric view (see Fig. 1 and Appendix A). As a result, 7 objects were represented in 4 unique views, and 5 in 3 unique views, where 2 views were redundant. To assess whether the tendency to view single versus multiple views was affected by the number of unique views representing an object, a 2×2 chi-squared test was performed. The insignificant result of this test ($\chi^2(1, 180) = 0.44$, $p = 0.5$) reveals that single versus multi-focused visual fixation was not affected by the number of unique views shown. Single versus multi-focused visual fixation was similarly unaffected by the size of objects ($\chi^2(2, 180) = 0.93$ and $p = 0.7$), categorized as small (key, paper clip, and push pin), medium (mug, brick, pencil, hanger, and screwdriver), and large (table, chair, barrel, and tire).

However, the specific representation of objects chosen may have otherwise affected visual fixation, due to the material and part composition of objects shown. Thus, we explored the difference in object-focus type in objects comprising three separate groups of different material and/or part configuration. The first has nonuniform material composition and includes push pin, barrel, pencil, and screwdriver. The second has uniform material composition with functionally different parts or features, including key, mug, hanger, chair, and table. The final group has uniform material composition and one main part, including paper clip, brick, and tire. Object-focus type was significantly different between these groups of objects ($\chi^2(2, 180) = 6.3$ and $p < 0.05$). Objects represented with nonuniform material composition were more likely viewed in multiple views, and objects with uniform material

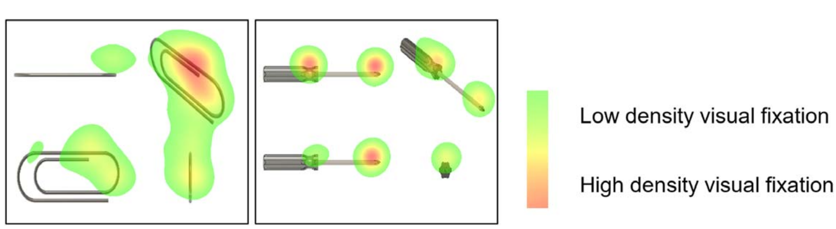


Fig. 5 Heat maps of visual-fixation duration of example single-focused (left) versus multi-focused (right) trials corresponding to low and high fluency scores

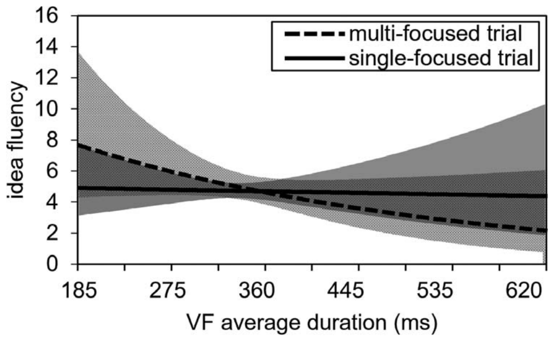


Fig. 6 Interaction effect between object-focus type (multi-focused versus single-focused) and VF average duration with 95% confidence intervals of predicted idea fluency

Table 6 Negative binomial regression model predictors of category flexibility ($n = 180$)

VF measure	β(Standard error)	Exp(β)	p
Significant predictors of category flexibility by trial			
Object-focus type[a]	1.3(0.36)	3.5	<0.001
Interaction effects			
Object-focus type[a] and VF average duration (ms)	−0.0035(0.0018)	0.99	<0.001

[a]Comparing multi versus single object focus.

composition in single views. These findings suggest that to isolate the effect of visual fixation toward multiple views on creativity, visual representation of objects should be consistent regarding part and material uniformity. Future work on the effect of object representation on AUT performance is recommended but is beyond the scope of the present work.

3.2 Event-Based (Silent Versus Response) Analyses. This section describes the event-based analysis of visual fixations during both silent events before, and response events while, naming alternative uses. The differences between speaking versus non-speaking events in each trial may cause variation in eye movements and visual fixation. Therefore, to isolate the relationship between divergent thinking and eye movements from the effect of speaking, silent and response events were analyzed separately. Unlike in the previous analysis where each trial always consisted of two minutes, the duration of each time-separated event varied. To account for these differences, VF proportion was calculated as the ratio of total visual-fixation duration over the total event duration. Also due to different durations, VF count was excluded from this analysis.

The following reveals how eye movements during either silent or response events were related to idea and category newness. Since these are binary measures, binary logistic regression models were used. In these models, where multiple events comprise each trial completed by each participant, repeated measures accounted for correlations between events. Visual fixations were defined in terms of VF average duration, VF proportion, object-focus type (none, single-focused, or multi-focused), weighted blank fixation, and weighted object fixation. Descriptive metrics of visual fixation during silent and response events are summarized in Table 7.

3.2.1 Silent Events. During silent events, weighted blank fixation and object-focus type (none, single-focused, or multi-focused) had a significant effect on category newness of the subsequently stated alternative use. No significant effects were observed for idea newness. These effects are summarized in Table 8.

Silent-event analyses revealed that thinking of an alternative use belonging to a new category was related to *both* attending to at least one view of the object *and* to increased visual fixation on blank space. Before naming an alternative use, looking toward at least one view of the object was more related to category newness than if no visual fixation on the object occurred. As mentioned earlier, when there was no visual fixation on the object, "none", i.e., no object-focus type, was assigned. There was no difference observed in category newness between multi-focused versus single-focused silent events (0.99 (95% CI: [0.63 and 1.56])).

Also observed in silent events before naming new categories of alternative uses was increased visual fixation toward blank space on the screen. The distinction between an event with an object-focus type of "none" and high weighted blank fixation is clarified in Fig. 9. The regression model estimates that by increasing blank visual fixation by 30% on a 75% blank screen, category newness is 1.32 times more likely (95% CI: [1.03, 1.71]). It should be noted that the lower bound of the confidence interval is close to 1, indicating that the effect of blank visual fixation on category newness may be smaller than that found in the current study. Future work with a larger sample size should be performed to verify the size of this effect.

The positive effects of increased time looking at blank space does not suggest that the object should be ignored. Discussed in greater depth later, increased visual fixation on blank space may support the internal representation of the object, especially if it is attended to within the same silent event as looking at the object. That is, increased visual fixation on blank space may not be relevant for thinking of new categories of ideas unless this is a result of looking away from the object. Alternatively, following a period of ideation while looking at blank space, participants may look at the object to reinforce or verify their ideas. The order of these events, missing from the present analysis, may in future clarify these findings.

3.2.2 Response Events. Visual fixations were also analyzed during response events, i.e., when alternative uses were named aloud. No significant effects were observed for category newness. Object-focus type had a significant effect on idea newness, as shown in Table 9.

When describing new alternative uses, visual fixation on one view of the object was observed more than no visual fixation on the object. No differences were observed between looking at multiple versus no object views (1.84 (95% CI: [0.87, 3.87])) or between looking at single versus multiple object views (0.90 (95% CI: [0.47, 1.73])). The likelihood that a new idea was being described

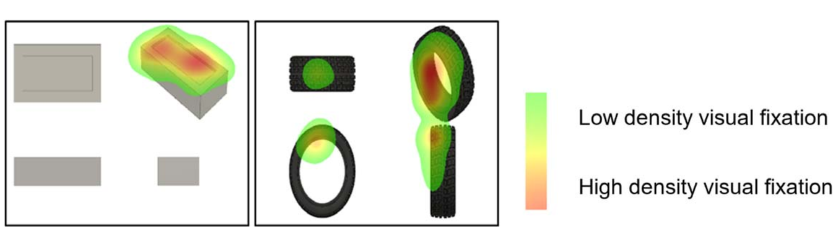


Fig. 7 Heat maps of visual-fixation duration of example single-focused (left) versus multi-focused (right) trials corresponding to low and high flexibility scores

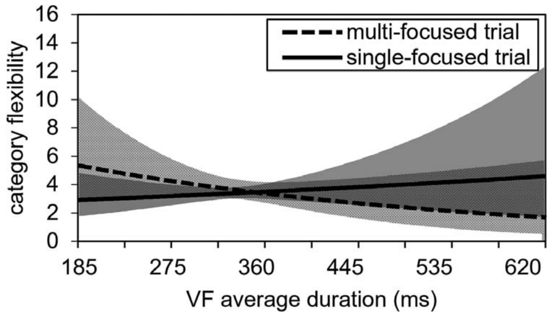


Fig. 8 Interaction effect between object-focus type (multi-focused versus single-focused) and VF average duration with 95% confidence intervals of predicted category flexibility

Table 7 Descriptive metrics of event-based analysis

VF measure	Median (min and max values)	Standard deviation
Descriptive metrics of silent events ($n = 1141$)		
VF average duration (ms)	302 (0, 1563)	152
VF proportion	0.75 (0, 2.2)	0.41
Weighted blank fixation	0.59 (0, 1.3)	0.40
Weighted object fixation	3.1 (0, 14)	2.4
VF measure	Median	Standard deviation
Descriptive metrics of response events ($n = 1141$)		
VF average duration (ms)	282 (0, 3514)	227
VF proportion	0.81 (0, 1)	0.21
Weighted blank fixation	0.64 (0, 1.3)	0.43
Weighted object fixation	2.7 (0, 14)	2.5

Table 8 Binary logistic regression model predictors of idea and category newness for silent events ($n = 1141$)

VF measure	β(Standard error)	Exp(β)	p
Significant predictors of idea newness for silent events N/A			
Significant predictors of category newness for silent events			
Object-focus type (single-focused versus none)	0.64(0.20)	1.9	<0.01
Object-focus type (multi-focused versus none)	0.65(0.33)	1.9	<0.05
Weighted blank fixation	0.71(0.32)	2.0	<0.05

increased by 1.66 times (95% CI: [1.06, 2.58]) when participants looked at a single view of the object than when the object was not attended to. As participants verbalized their responses and continued to develop their ideas, overcoming idea fixation was associated with continuing to gain visual information about the object. Again, the closeness of the lower bound of the confidence interval to 1 may indicate that there was a small difference between looking at one and no object views. Using a larger sample size in future work may verify the significance of this difference.

4 Discussion

Both trial- and event-based analyses of eye movements observed during the AUT support that visual fixation is related to idea fixation. Addressing our research questions, our results reveal:

(1) eye-movement behaviors observed when viewing visual stimuli;
(2) cognitive processes underlying divergent thinking; and
(3) insights into developing methods that enhance divergent thinking.

While deriving alternative uses for common objects, dividing visual fixation across multiple views of the object was related to reduced idea fixation, expressed in higher AUT fluency and flexibility. Also related were shorter visual fixations when looking at multiple views of an object and longer visual fixations when looking at a single view of an object. In event-based analyses, looking at blank space was observed before deriving new ideas. These results provide insight into how using visual stimuli may encourage divergent thinking as well as what cognitive processes may be involved in overcoming idea fixation.

4.1 Behaviors Observed When Viewing Visual Stimuli.

Contradictory prior research regarding effective AUT object representation motivated the analysis of visual-fixation locations. Showing multiple views of an object may support the need to study its visual features by providing more, and more varied, ways to do so. Viewing a single representation of an object might also be helpful when thinking of its alternative uses. Instead of providing multiple views, a single view might invoke the mental transformation of the object in multiple ways. The present study supports the effectiveness of both ways of using pictorially represented AUT objects.

Based on our results, looking at multiple object views when specifically thinking of a new idea was not necessarily more beneficial than looking at only one object view. In contrast, when describing an idea, visual fixation on only a single view was observed. However, when multiple views, rather than a single view, of an object were attended throughout a trial, participants named more new ideas and categories of ideas. Intuitively, different object representations provide more inspirational stimuli for ideation. Additionally, the specific material and part composition used to represent objects may also affect whether they are viewed in single or multiple views across a trial. Looking at multiple views of objects was more likely when the object was shown with multiple parts and materials. Thus, if looking toward multiple object views throughout a trial is beneficial for new-idea generation, this behavior may be enhanced by representing objects with more complexity, which may encourage visual fixation on more views of an object. Using eye tracking to detect disproportionate visual fixation on a single view of an object, increased sampling of visual stimuli could also be achieved by cueing designers toward other views. Looking at less-explored representations of the object might help avoid idea fixation and enhance creative thinking.

4.2 Cognitive Processes Involved in New-Idea Generation.

While the tendency to view multiple object representations could be an outcome of a behavioral strategy, i.e., to gain more relevant information, many of the eye-movement behaviors observed more importantly give insight into the cognitive processes involved in divergent thinking. For example, also relevant to these results is looking-at-nothing behavior. Visual fixation on blank space that previously displayed object stimuli has been found by Ferreira et al. to facilitate retrieval of information about the object from memory [50]. Increased visual fixation on blank space before new-idea generation may similarly suggest retrieval of information associated with the object from memory. This process was also revealed in a neuroimaging study by Goucher-Lambert et al., in which inspirational stimuli were given in a design task [51,52]. In their study, thinking about the inspirational stimuli and making connections with associated concepts retrieved from memory helped stimulate new ideas. This result supports our interpretation that participants who named new ideas after looking at blank space were similarly engaged in memory-retrieval processes. These findings further coincide with eye-tracking work by Salvi et al., who observed increased blinking and eye movements away from external stimuli during insight-problem solving [53]. Eye movements

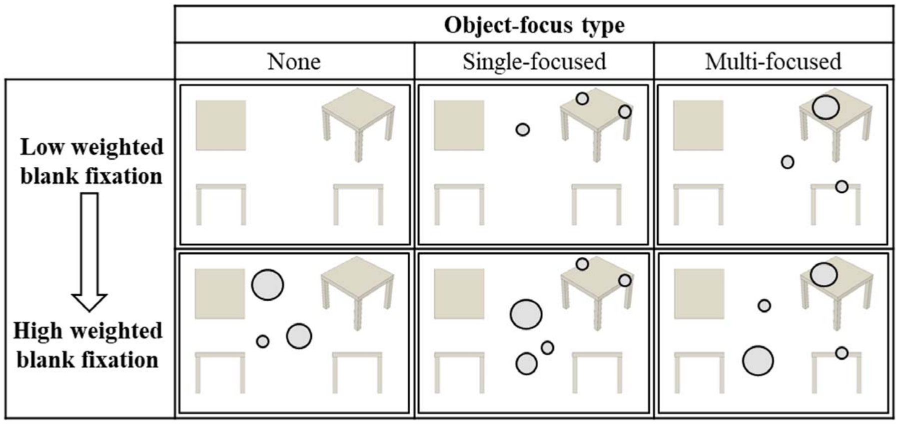


Fig. 9 Weighted blank fixation versus object-focus type: circles represent visual fixations in events corresponding to low versus high weighted blank fixation (top versus bottom) and none versus single-focused versus multi-focused object-focus types (left to right). Larger circles represent more instances of visual fixation.

Table 9 Binary logistic regression model predictors of idea and category newness for response events ($n = 1141$)

VF measure	β(Standard error)	Exp(β)	p
Significant predictors of idea newness for response events			
Object-focus type (single-focused versus none)	0.50(0.23)	1.7	<0.05
Significant predictors of category newness for response events			
N/A			

observed in these studies as well as in our presently discussed work are indicative of internally directed attention.

In summary, we propose that the looking-at-nothing and gaze-aversion behaviors observed are reflective of cognitive strategies used for enhanced divergent thinking and reduced idea fixation. These cognitive strategies involve internally directed cognition (IDC), which facilitates retrieval of object-related information from memory and formation of new mental associations about the object [54].

4.3 Furthering Design Research. This study was conducted to observe eye movements during the AUT, revealing both behavioral and cognitive processes involved in overcoming idea fixation. Based on the results discussed, we make the following contributions to and recommendations for design research.

4.3.1 Future Eye-Tracking Work in Creativity. Our study examined visual fixations across both two-minute trials and shorter time periods (events) preceding and during responses in the AUT. The trial-based analysis examined visual fixations related to overall task performance. The event-based analysis enabled a narrower glimpse into eye movements that occur during idea generation. Beyond the current study, many insights remain to be gained by monitoring eye movements, or other observable physical behaviors, during a creativity task. Such work also motivates continued collaboration between cognitive-psychology and engineering-design researchers.

The expanse of potential research is driven in part by the wealth of available data in an eye-tracking study, related to different types of eye movements. While visual fixations were the focus of the current work, unexplored aspects include the number and duration of short, spatially distant eye movements (saccades) and blinks. Also worth further exploration are distances between and direction of eye movements. Looking away from objects during the AUT was correlated with an increased likelihood of naming a new idea, but does how far away have an effect?

Our analyses provided the opportunity to identify visual fixations related to naming a new idea or an idea belonging to a new category. Future work could also compare eye movements related to other desirable design outcomes such as increased novelty or originality.

4.3.2 Strategies to Enhance Divergent Thinking in Design. The results presented provide insight into the cognitive processes involved during divergent thinking and new-idea generation. We propose that these processes are related to IDC which enables retrieval and recombination of object-related information during the AUT. Below, we suggest how the development of tools and strategies to enhance divergent thinking can incorporate these and other findings.

Interventions that manipulate the visual stimuli used to present a design problem could help facilitate these cognitive processes. In a review of design research, Vasconcelos and Crilly discussed the effect of external stimuli on design fixation [55]. Depending on the design problem, design fixation can be reduced by changing the properties of external stimuli such as modality of representation, timing of their presentation, quantity, and proximity to the design problem. The present study reveals that attending to multiple views co-occurs with overcoming idea fixation. Related to quantity of stimuli, one suggestion is that increasing external stimuli may help mitigate fixation effects in divergent thinking. Alternatively, it may be that the presence of multiple task-relevant stimuli is useful due to close problem proximity. It is uncertain whether looking at multiple views is effective in overcoming fixation because an increased quantity of stimuli is itself useful, or if it enables a gain in task-relevant information. To fully explain the role of these factors on divergent thinking in design, direct comparisons between multiple versus single and task-relevant versus irrelevant stimuli should be made.

On the other hand, one interpretation of the observed visual fixation toward blank space is that it is reflective of cognitive processes involving IDC. Reducing the exposure to external stimuli on which to visually fixate may enable these processes, which support divergent thinking in design. Instructional strategies encouraging retrieval of past knowledge or experiences related to the design problem, particularly during moments of idea fixation, also require future work.

5 Conclusion

The current study investigated the relationship between eye movements and performance during the AUT and whether visual fixation affects idea fixation. Broadly, we found that visually fixating on multiple views of an object instead of only one of its views is related to decreased idea fixation. More specifically, shorter visual fixations when looking at multiple views and longer visual fixations on a single view of an object are each related to greater fluency and flexibility of alternative uses. Before naming alternative uses belonging to new categories, participants were observed to increase both visual fixation toward blank space and visual fixation on at least one view of the object. This study suggests that visual fixation is indeed related to idea fixation and reveals the specific eye movements related to divergent thinking.

We present evidence not only for a generic relationship between visual fixation and idea fixation but specifically for eye movements characterizing IDC during new-idea generation. Our analysis helps identify when such thinking is useful in the process of ideation. The looking-at-nothing behavior observed before generating new ideas may be a marker for internal retrieval of existing knowledge related to the object. While design fixation and functional fixedness, and thus remembered examples, are to be avoided, memory retrieval is likely important in creativity. When thinking of and vocalizing new alternative uses for an object, visual fixation on it, possibly related to studying its visual features, is also important.

Eye movements, as expected, reveal how objects represented by visual stimuli are viewed during the AUT. However, eye movements also reveal the internal cognitive processes reflected by visual fixation. Both these insights may be important when developing interventions to enhance creativity and overcome fixation to recently thought-of ideas. That is, visual stimuli can be designed to specifically support divergent thinking when generating ideas, e.g., by increasing the diversity of visual representations and opportunities for looking away from visual stimuli. Intuitively, idea fixation should be overcome by forgetting old ideas. In contrast, the visual-fixation behaviors we observed suggest that *enabling* memory retrieval is also key to overcoming idea fixation.

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Nomenclature

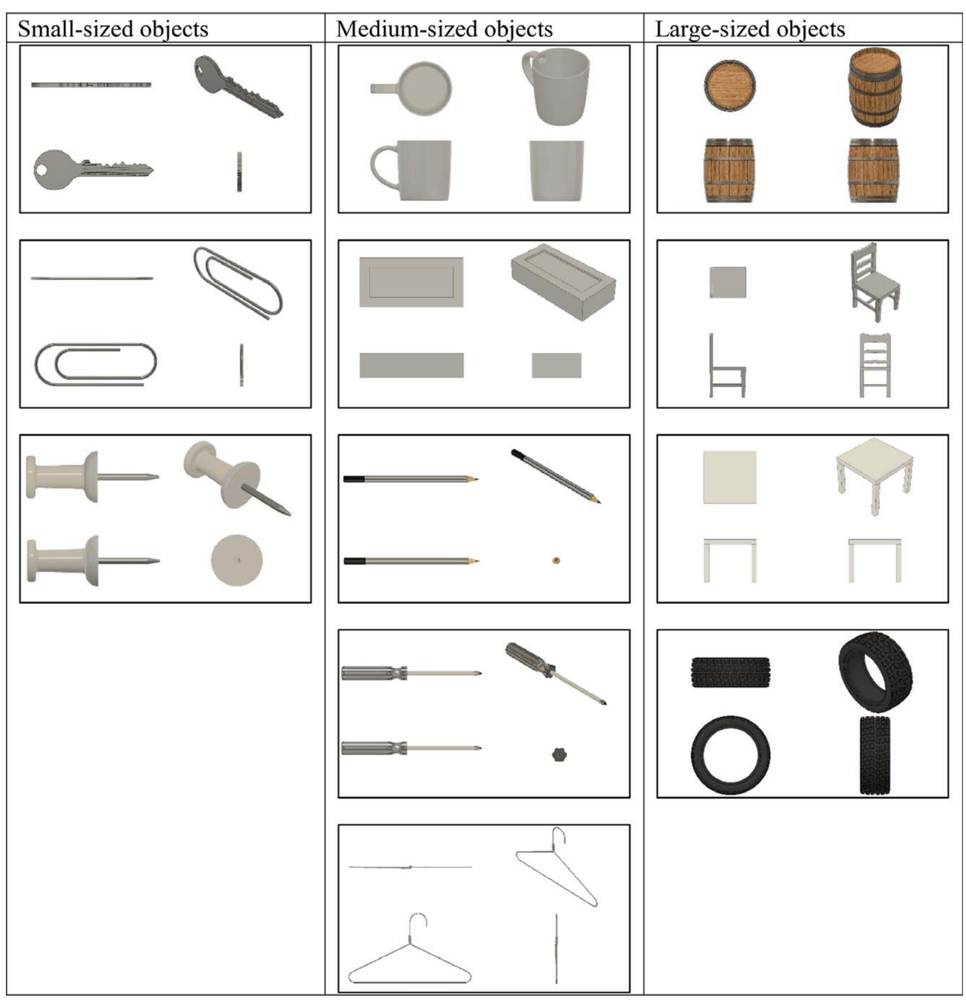
Visual fixation = spatially fixated eye movements (within 0.5 deg visual angle)

Idea fixation = repeating previously thought-of ideas

Alternative Uses Test (AUT) = divergent-thinking test in which alternative uses are named for common objects [1]

Internally directed cognition (IDC) = processes that build on memory rather than sensory input to generate novel mental representations [37]

Appendix A: Visual Stimuli Provided for Objects



Appendix B: Categories of New and Repeated Alternative Uses

For Participant #3, the following list of categories of alternative uses were identified, with examples of new versus repeated alternative uses belonging to each category also listed.

Categories of alternative uses	Alternative-use example	Repeated alternative-use example	New alternative-use example
Break with	Break a window	To break a window	To break down the door
Pressing button	Open your phone	Open your phone	
Climbing pick	Climbing a cliff		
Decoration	Decoration	To decorate	
Door lock	To prevent a door from being opened		To prevent someone from getting in if you put a chair up against a door
Door stop	Door stopper	As a door stopper	
Eating utensil	Eat food with it		
Exercise equipment	You can use it to work out	You could exercise with it	
Fuel	To burn to start a fire		
Hairclip	As a hairclip		
Hammer	As a hammer		
Hang off of	To hang clothes on	Holding clothes on it	Draping a tent over
Hiding spot	To hide in		To hide underneath
Holder	Hold things in		Hold pencils
Holding together	Holding things together		
Jewellery	Wear as a ring		
Keychain	As a keychain		
(knife) Cutting	Rip something open	Rip anything open	Opening packages
(knife) Stabbing	Stabbing something		
Landmark	A landmarker type thing		
Lifting weight	Weights for working out		Retrieving weights from a pool for lifeguard training
Make hole	Putting a hole in something		Ear piercing
Measure	Measure something brick-sized		As a ruler
Musical instrument	Tap a drum with		
Pointer	Point to something		
Pusher	Pushing something into a tight spot		
Reacher	Pick up something you can't reach		Getting something out from a tight spot
Wreath	Christmas wreath		
Rolling pin	Roll dough with		
Setting weight	Paper weight	Paper weight	Weighing things down so things do not float away
Step	Step ladder	As a ladder	
Swing	Swing		
Trace	Trace a straight line	Draw a straight line	Trace a circle
Weapon	Killing someone	Stab someone with it	
Working surface	As a side table		

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