RE-EXAMINING THE IMPACT OF ANALOGIES ON IDEATION SEARCH PATTERNS: LESSONS FROM AN IN VIVO STUDY IN ENGINEERING DESIGN

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Chu Sern Joel Chan

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This thesis was presented

by

Chu Sern Joel Chan

It was defended on

January 18, 2012

and approved by

Timothy J. Nokes-Malach, Assistant Professor, Department of Psychology

Kenneth Kotovsky, Professor, Department of Psychology, Carnegie-Mellon University

Jonathan Cagan, Professor, Department of Mechanical Engineering, Carnegie-Mellon University

Thesis Director: Christian D. Schunn, Professor, Department of Psychology

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Decades of research on the cognitive science of innovation have consistently implicated the importance of analogy during creative ideation. While the association of analogies with innovative design concepts is clear, more work is needed to understand the specific mechanisms by which analogy might help designers generate such concepts. The present work employed detailed analysis of the temporal interplay between analogy use and ideation in the naturalistic brainstorming conversations of a real-world professional design team to test between competing hypotheses in the literature: (1) analogy supports innovation primarily via large steps in design spaces during concept generation (jumps), and (2) analogy supports innovation primarily via small steps (incremental search). In Study 1, self-generated analogies (including distant ones) were not systematically associated with jumps; on the contrary, concepts tended to be more similar to their precedents after analogy use in comparison to baseline situations (i.e., without analogy use). Study 2 found that the rate of concept generation was greater when associated with analogy in comparison to baseline conditions, suggesting that the effects observed in Study 1 were not due to an overall fixating effect of analogies. Overall, these results challenge the view that analogies help designers generate innovative concepts mainly via jumps in design spaces, and instead suggests that analogies primarily support incremental search. Theoretical implications and future directions for the cognitive science of analogy and innovation are discussed.

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PREFACE

The road to this thesis has been exhilarating, frustrating, long, and ultimately fulfilling. I have many people to thank for me eventually reaching this point: Chris Schunn, my fearless and eminently creative advisor, for introducing me to this exciting and challenging study of the cognitive science of innovation, and for his invaluable guidance, encouragement and patience as I searched the large spaces of possible hypotheses, experiments and analyses to address my research questions; Bo Christensen and Linden Ball for sharing this dataset with me and providing feedback on the conceptualization of the study; my committee members, Tim Nokes-Malach, Ken Kotovsky, and Jon Cagan, for lending their time and expertise to help me think through conceptual and methodological challenges with the work; the many industrious and bright research assistants, including Nick Rassler, Sophia Bender, Adam Sparacino, Matt Oriolo, Oreste Scioscia, and Stephen Denninger, who helped with data processing and/or coding; Tom Stephenson for introducing me to the science of psychology, the American Psychological Association, Greg Trafton, and Raj Ratwani for introducing me to cognitive science, and Joel Hagaman for supporting my initial forays into independent research in this field; and finally, God, my family, and Anna, my wife, for their unwavering support for me as a person and budding researcher. May this thesis be but one step in a lifetime's journey down the unpaved roads of discovery.

1.0 INTRODUCTION

Where do innovative design concepts come from? In decades of research on this question, researchers and theorists have uncovered the importance of collaboration and serendipity (Sawyer, 2007), incubation (Christensen & Schunn, 2005; Seifert, Meyer, Davidson, Patalano, & Yaniv, 1995; Tseng, Moss, Cagan, & Kotovsky, 2008), sketching and design tools (Goel, 1995), and mental simulation (Christensen & Schunn, 2009), among others. The present work focuses on analogy, another relevant cognitive process.

Analogy is a fundamental cognitive process in which a *source* and *target* domain of knowledge are linked to one another by a systematic mapping of attributes and relations, which then allows for transfer of knowledge to the target (Holyoak & Thagard, 1996). This process appears to be important for creative thinking in a wide variety of domains, including management problem-solving, politics, scientific reasoning and discovery, and artistic creation (Bearman, Ball, & Ormerod, 2002; Blanchette & Dunbar, 2001; Dunbar, 1997; Markman & Wood, 2009; Okada, Yokochi, Ishibashi, & Ueda, 2009).

With design, too, there is substantial evidence that innovative designers often analogize from other domains of knowledge, such as prior design experiences, everyday artifacts, or biological artifacts and systems, to the design problem they are working on. Documented examples of innovative designs based on analogies include a retractable mast with sail designed by analogy to bird and bat wings, and water-filled travel weights by analogy to air mattresses

(Linsey, Laux, Clauss, Wood, & Markman, 2007), and George Mestral's invention of Velcro by analogy to burdock root seeds, among many others. Protocol analyses of professional designers' naturalistic ideation processes have also shown that analogy is a frequently used strategy, at approximately 11 per hour by some estimates (Ball & Christensen, 2009; Christensen & Schunn, 2007; Dahl & Moreau, 2002). Experimental studies of design ideation have also documented positive impacts of analogy on novelty of design concepts (Chan et al., 2011; Dahl & Moreau, 2002; Goldschmidt, 2001; Vargas-Hernandez, Shah, & Smith, 2010; Wilson, Rosen, Nelson, & Yen, 2010).

Despite the substantial evidence linking analogy to innovative design outcomes, fundamental questions remain. What kinds of analogies lead to innovative concepts? At which points during ideation are they most helpful? And, perhaps most fundamentally, how do analogies actually help designers generate innovative design concepts?

1.1 DESIGN IDEATION AS SEARCH IN A SPACE

To gain traction with these questions, it is fruitful to first consider what the literature has to say about creative ideation in general. One theoretical characterization of conceptual ideation has been that of a search in a space (Boden, 2004; Goel & Pirolli, 1992; Perkins, 1994; Simon, 1996). The general formulation of problem-solving as heuristic search in a problem space (Newell & Simon, 1972) has been applied in similarly complex domains, including theorem-proving (Newell, Shaw, & Simon, 1958) and scientific discovery (Klahr, 2000; Shrager & Langley, 1990). A problem space is defined in terms of states of problem solving, operators that move the problem solving from one state to another, and evaluation functions for testing the difference between current states and goal states. This abstract problem space is distinguishable from the external task environment, and is commonly held to be represented in the problem solver's internal memory (Newell & Simon, 1972). Problem solving activity includes formulation of the problem space and traversal of the problem space between states via operators, punctuated by evaluation functions that test for differences between the current state and the goal state. This formulation of search in a space has been extended to design in particular; design ideation can be construed as a constrained search in a design state space, where each state is a particular design configuration that can be compared against a list of design requirements (Campbell, Cagan, & Kotovsky, 2003; Gero & Kazakov, 1998; Goel & Pirolli, 1992).

Broadly, there are two forms of heuristics or operators. "Strong methods" are domain-specific operators that considerably reduce search by taking advantage of knowledge about the constrained structure of the task environment. Examples include experimental paradigms in science and retrieval of classic move-situation pairs in chess, among others. In contrast, "weak methods" are domain-general but involve considerably more search, such as hill-climbing and means-ends analysis (Newell & Simon, 1972). Analogy can be seen as one such "weak method".

1.2 ANALOGY AND PATTERNS OF SEARCH

We can now frame the question of how analogies might aid in the generation of innovative concepts in terms search operator character. The literature provides two conflicting answers: (1) analogy is primarily a "jump" search operator, and (2) analogy is primarily an incremental search operator. These views will be discussed in turn.

1.2.1 Jumps in conceptual ideation.

One major assertion in the literature is that analogies enable "jumps" in the conceptual ideation space, an immediate move to a more conceptually or functionally distant region of the problem space. Several lines of argument support this assertion. First, theoretical accounts of analogy describe it as a central cognitive mechanism for bridging seemingly disparate conceptual spaces, enabling thinking across categories and implicit conceptual boundaries (Gentner, 2003; Hofstadter, 2001; Holyoak & Thagard, 1996). The process of analogy has been computationally described and implemented in slightly different ways among theorists, but consensus exists that the core process in analogy involves the alignment of disparate knowledge structures based on relational structure (French, 2002; Gentner & Forbus, 2011). Importantly, the power of analogy is most strikingly demonstrated when knowledge structures are aligned based on higher-order relations, such as "cause", "enable", or "constrain", which can be abstracted at a high level from domain-specific features and objects.

Examples of the involvement of analogy in invention and innovative design from the history of technology also often fit a common pattern of moving from one domain of search to another in one step. The novel solution to the design of boat sails was found by analogy to bat wings, linking the domain of sailing to the domain of biology; the solution to the need for a novel connective (Velcro) was found by an unexpected analogy to burdock root seeds, linking synthetic connectives to the domain of biology. Numerous other anectotal examples exist.

One important thing to notice is that all of these examples involve *distant* analogies (i.e., a low degree of overlap of surface elements). These sorts of analogies are contrasted with more *local* analogies that involve a higher degree of overlap between both structural features and surface elements. It is often emphasized in the literature that the potential for innovative outcomes is strongest when distant analogies are involved in ideation (Gentner & Markman, 1997; Markman & Wood, 2009; Ward, 1998). Accordingly, empirical studies have found correlations between distant analogizing and innovative outcomes. For example, Dahl & Moreau's (2002) study of analogizing in professional designers discussed above showed a positive link between distant analogy use and rated originality of the designers' proposed solutions. Similarly, Chan and colleagues (2011) showed in a study of design ideation with engineering design students that distant analogies were linked to increased novelty of solution concepts.

One final line of evidence comes from the interest from professional engineering practice in formalized design-by-analogy methods, such as Synectics (Gordon, 1961)—group design through analogy types; French's (1988) work on inspiration from nature; and Biomimetic concept generation (Hacco & Shu, 2002)—a systematic tool to index biological phenomena that links to textbook information. These analogy methods are seen as ways of maximizing the probability of generating innovative concepts.

Given these converging lines of evidence from the theory of analogizing, history of technological inventions, and empirical studies, there does seem to be a case for analogy as a jump operator, particularly when analogical distance is high. However, there is also evidence in the literature for an alternative characterization of analogy's role in innovative search, where the thinker employs analogy to traverse the problem space in incremental steps, the accumulation of which eventually results in an innovative concept.

1.2.2 Incremental search.

One line of evidence for analogy as an incremental operator comes from the arguments of theorists analyzing the history of invention. For example, Weisberg (2009) has argued for an incremental view of the role of analogy in invention, pointing to examples like the Wright brothers' invention of the airplane steering system by analogy to bicycles. More direct empirical evidence comes from Dunbar's (1997) pioneering studies of four top-performing microbiology labs. His data collection and analyses focused on "on-line" thinking and reasoning during lab meetings. Dunbar observed major scientific discoveries (that were later published in top-tier journals) as they happened, and his analyses of the meetings revealed that conceptual transformation did not occur in single, conceptual jumps, but rather arose from an accumulation of smaller mutations in concepts, often fueled by numerous analogies to other experiments on the same organism or organisms with prominent homologies.

A related view of analogy emerged from Okada and colleagues' (2009) studies of the long-term creative processes of eminent contemporary artists. They found that their artists often generated novel artistic creations via an incremental process they called "analogical modification", which involved generating a new target based on an existing source by modifying one or two key relations or objects in the mapping. For example, one artist's creative vision was to explore the possibility of multiple different views of the world. His initial collection of artworks centered around the concept of "erasing the meaning", where he would erase a character or a thing from an original piece, such as ancient Japanese picture scrolls and Bach's musical notes. This artist later developed a novel collection of artworks centered on the concept of duplication, in which he duplicated persons or things in postcards or photographs of scenery. Importantly, the conceptual distance between the two artwork collections was relatively close:

both involved applying a single modification to an existing artwork while leaving the rest of it unchanged, and differed mainly in the specifics of the modification used. Okada and colleagues reported other case studies that followed a similar pattern.

The process of analogical modification observed by Okada and colleagues is similar to the computational modeling efforts of Hofstadter and the Fluid Analogies Research Group (1995) to computationally model the creation of new features and concepts via "conceptual slippage", where a mapping of an object A in one domain to an object B that has a different role from A in another domain results in a "slippage" of the objects into neighboring concepts in order to improve the analogical match. A similar process of re-representation of concepts exists in Gentner and colleagues' computational models of analogical modification of concepts, where certain portions of the source knowledge structure can be modified to improve analogical match with the target knowledge structure, or vice versa (Gentner, 2010; Gentner et al., 1997).

1.3 SUMMARY

In summary, the literatures on analogy, creativity, and innovative design have collectively offered two alternative characterizations of the way that analogies can help designers generate innovative concepts during ideation. On the one hand, analogy can be viewed as primarily supporting mental jumps in the design space to innovative concepts. On the other hand, analogy can also be viewed as primarily facilitating incremental steps through promising regions of the design space, the accumulation of which eventually lands the designer at a portion of the design space much different from where s/he started. Which of these characterizations best explains the role of analogy in creative design ideation? It could be that analogy either primarily supports jumps or incremental steps, but not both. It could also be that analogy supports search by both jumps and incremental steps, depending on other variables, such as analogical distance and problem difficulty.

As the review of evidence for either view above suggests, the literature at present still needs further empirical work to decide which of these characterizations is correct. Prior studies showing a positive effect of distant analogies on novelty of ideation have typically done so in an "input-output" design, where the ideation *outputs* of designers who are given analogies as stimulation are compared to those of designers who are not given analogies. The lack of "online" process data still leaves open the possibility that the designers in the analogy groups may be chaining together analogies and generated concepts to incrementally arrive at novel concepts in a way that is not recorded in their final recorded designs. Additionally, historical studies and introspective/retrospective interviews of prominent creative individuals carry the risk of distortion from reconstructive processes in retrospection and introspection. Finally, online studies of the creative process have not measured and analyzed analogy use and ideation search patterns together. The purpose of the present work was to assist in addressing this gap in the literature via detailed analyses of the online interplay between analogy and ideation processes of real-world professional designers.

2.0 STUDY 1

2.1 OVERVIEW

Detailed analyses were conducted on the temporal interplay between analogy use and ideation events in the naturalistic brainstorming conversations of a real-world professional design team. The team was tasked with developing a new product concept for a hand-held application of thermal printing technology for children. These conversations unfolded over the course of two design team meetings; the first meeting lasted 1 hour and 37 minutes, and focused on mechanical design sub-problems; the second meeting lasted 1 hour and 40 minutes, and focused on electronics sub-problems. The design team comprised 7 professionals from different design sub-disciplines, including one from electronics and business development, four from mechanical engineering, one from business consulting, one from ergonomics and usability, and one from industrial design and project management.

The purpose of Study 1 was to investigate two alternative hypotheses about whether analogy use was associated more with jumps or incremental steps in the functional distance of concepts during concept generation:

Hypothesis 1a: The functional distance of a proposed concept from concepts recently considered will be reliably greater when preceded by analogies vs. baseline, i.e., when not preceded by analogies.

Hypothesis 1b: The functional distance of a proposed concept from concepts recently considered will not be reliably greater when preceded by analogies vs baseline.

It should be noted here that, given the naturalistic character of the data, ideation search patterns following analogy is not compared with standard "control" no input conditions, but more precisely against functional distance of search when the designers were not using analogies; other solution generating strategies were more than likely being employed, such as reasoning from first principles and mutation of existing concepts (Ullman, 2002).

2.2 METHODS

2.2.1 Segmentation.

Analysis was conducted on the transcribed audio from the two meetings. Transcripts were segmented into lines by utterances, such that each line contained a separate thought; in this segmentation, a single sentence or speaker turn could span multiple lines. The segmentation procedure resulted in a total of 4,594 lines, 2,382 in the first meeting, and 2,212 in the second.

2.2.2 Coding.

2.2.2.1 Analogy use.

Coding of analogy use was conducted by a prior research team, whose findings have been published in Ball and Christensen (2009). Analogies were coded at the sentence/turn level, but tagged at the line level, meaning that analogies often spanned multiple lines. Sentences were coded as analogies any time a designer referred to another source of knowledge and attempted to transfer concepts from that source to the target domain. 144 analogies were found across the 2 transcripts (79 in the first and 65 in the second), with an inter-rater reliability of (Cohen's kappa) $k = .77$.

Analogies were coded for both distance and purpose. Following previous work examining analogical distance (Ball & Christensen, 2009; Christensen & Schunn, 2007), distance was coded at two levels: *local* analogies involved mappings from sources that related to tools, mechanisms and processes associated with graphical production and printing, while *distant* analogies involved mappings from more distant sources (see Tables 1 and 2). Of the 144 analogies found, 16% were coded as local, and 84% were coded as distant. Inter-rater reliability was very high, $k = .99$.

Table 1. Example of local analogy

976	Alan	the other thing to to think about is
977		in almost all cases when I look at pens the apart from re-wired sort of micropens the th- tip is actually the narrowest part of the product
978		whereas in what we're looking at it could actually be as wide or wider-

Table 2. Example of distant analogy

1520	Tommy	like a garage door type of thing
1521	Todd	yeah push the button
1522		then it goes open

Following previous work (Ball & Christensen, 2009; Blanchette & Dunbar, 2001; Christensen & Schunn, 2007), analogical purpose (i.e., the goal or function of the analogy) was coded at 3 levels, with a 4th level added as a theoretical contribution by Ball and Christensen (2009; see Tables 3-6 for examples): (1) *Problem identification* - noticing a possible problem in the emerging design, where the problem was taken from an analogous source domain, (2) *Concept generation* - transferring possible design concepts from the source domain to the target domain, (3) *Explanation* - using a concept from the source domain to explain some aspect of the target domain to members of the design team, and (4) *Function-finding* - active mapping of new functions to the design form currently being developed (i.e., a thermal printing pen). Inter-rater reliability for this coding scheme was high, $k = .85$.

Table 3. Example of problem identification analogy

1204	Alan	in fact in some ways we should think about the fact it isn't even a pen
1205		because a pen you you'll always learn to write from left to right
1206		whether you're left handed or right handed
1207		so actually what you end up doing with left handed people is you smudge over over your work
1208		which is a problem
1209		but actually with this you're dragging it
1210		you're not pushing it are you
1211		most people will drag it

Table 4. Example of concept generation analogy

1520	Tommy	like a garage door type of thing
1521	Todd	yeah push the button
1522		then it goes open
1523		yeah

Table 5. Example of explanation analogy

213	Tommy	yeah this is a bit like photographic paper in a way
214		where you're erm developing what's on the paper
215		whereas here you're just enabling the bits you need to print
216		so here you're kind of getting in to normal text

Table 6. Example of function-finding analogy

1160	Todd	um that's intriguing
1161		sort of like a like a could be like a finger puppe couldn't it
1162	Sandra	yeah cos wearing it like a finger puppet –
1163		the feel of it might be fun
1164	Todd	exactly so you can make you can make the footprints-

2.2.2.2 Concepts.

Three coders, including the author and two trained research assistants, identified generated solutions and then the sub-problems they were intended to address. Similar to the coding of analogy use, solutions were coded conceptually at the sentence/turn level, but tagged at the line level. Sentences/turns were coded as concept proposals any time a designer described a proposal for how to accomplish some design sub-problem, where a design sub-problem was defined as either (1) something the device (or a sub-system of it) has to do for the user (e.g., print, teach how to write, keep user's hands safe, make learning fun, make it harder to mess up, etc.), or (2) something the device or sub-system has to do to support or enable other functions (e.g., keep the print head level so that the print head mechanism can work). Defining concepts at the sub-problem level provided external validity to the coding scheme, given the primary focus on conceptual ideation processes, since ideation in professional engineering practice routinely occurs following decomposition of an overall design problem into sub-problems which are then addressed iteratively, sometimes in tandem (Ullman, 2002)

To avoid tagging of concept discussion lines as concept generation instances, only utterances that explicitly participated in a description of how a concept is meant to work were tagged as part of a concept; neither utterances evaluating concepts nor mere mentions of concepts (e.g., "that 'sheath idea' you mentioned earlier") were tagged as part of concepts unless they were embedded within a sentence or turn describing a concept. Identification of concepts utterances was done at an acceptable level of reliability: averaged k across the three coders was .72.

To provide a further constraint on identification of concept utterances, coders also simultaneously proposed a segmentation for a coherent group of concept utterances into intact concepts, and also proposed a pairing with one more sub-problems the concept was intended to address. Segmentation and pairing of concept utterances was then finalized by discussion during consensus meetings involving all three coders. In total, 217 unique concepts proposed for 42 sub-problems were identified. Examples of sub-problems included "keep the print head level", "specific application concept of product", "protect the print head", "power/energy saving", "user interface for controlling print options", "prevent overheating", "keep print head clean", "form of media", and "make device work for left-handed users".

Table 7 provides an example of a proposed design concept for the sub-problem "keep the print head level". This sub-problem was a major one discussed by the designers, and 35 distinct concepts were proposed for addressing it. The core of this sub-problem was that the thermal printing technology required that the thermal print head interfaced with the printing media within a strict range of angles in order for printing performance to be acceptable, and that the target market for the product concept, i.e., young children between the ages of 5 and 7, were judged as particularly unlikely to hold pens and writing devices in stable ways.

Table 7. Example concept for "keep the print head level"

690	Alan	( ) can I just explore that last one in a little more detail
691		because when organisations- making sure they can only be correct in one way
692		so the design and shape of the thing so it can only be done in one way
693		and that's the correct way
694		because then there is less sort of learning to be done by the user

The solution proposed in Table 7 was essentially a forcing function that would (via the shape of the device) force a particular way of holding the device that would ensure appropriate angles of contact.

2.2.3 Constructing ideation spaces.

To characterize the designers' search patterns during ideation, it was necessary to first characterize the search spaces. Since functional distance of concepts within the search space was the focus, a functional similarity space for concepts within each sub-problem space was constructed via pairwise comparison ratings of functional distance for each concept in each sub-problem space. That is, within each sub-problem space (e.g., "keep the print head level"), all concepts generated by the designers were rated for functional distance from all other concepts addressing the same sub-problem.

Two senior engineering undergraduate students conducted the pairwise ratings of functional distance. Functional distance between pairs of concepts was rated on a scale ranging from 1 to 5. Distance coding was conceptualized as a degree of overlap rating, with the following anchor points: 1 = very similar (very substantial overlap, only trivial differences), 2 = somewhat similar (substantial overlap, but some nontrivial differences), 3 = somewhat different (some overlap, some differences), 4 = (little overlap, numerous differences), and 5 = radically different (very minimal/trivial overlap).

The coding procedure was as follows. For each sub-problem space, the two coders together first looked through the list of proposed concepts in the space, and discussed and came to a consensus on an initial set of important points of contrast for comparing solutions. For example, for concepts proposed for the sub-problem "keep the print head level", one point of contrast was "user vs. device-centric approach (e.g., user-centric would be "give feedback to user and user adjusts accordingly", vs. "device has suspension system that adjusts for user action automatically"). Next, the coders independently generated functional distance ratings for all pairwise comparisons within the sub-problem space, using the points of contrast as a guide for their judgments. The final step involved computations of inter-rater agreement and discussion of disagreements greater than 1-point difference; differences of 1-point were averaged to produce a final distance rating. Inter-rater reliability was very good, with a mean inter-correlation of $r = .80$ across sub-problem spaces.

It should be noted that not all concepts entered into the analysis. Because the current analysis was focused on movement within an ideation space, sub-problems with less than 4 proposed concepts were excluded. The final set of concepts for analysis included 135 proposed concepts for 9 major sub-problems (see Table 8).

Table 8. Sub-problems by number of concepts

Sub-problem	# concepts
Keep the print head level	35
Specific application concept of product	35
Protect the print head	29
Acquiring print patterns	9
Powering the device	7
User interface for controlling print options	6
Varying print options available to user	6
Ensure print head only fires when on media	5
Maintain appropriate surface area of contact between print head and media	3

2.2.4 Analysis: Measures and model parameters.

One-way analysis of variance (ANOVA) models were employed to test the hypotheses, where each concept was the unit of analysis, with functional distance from prior reference point as the dependent measure and a 3-level "analogy before" between-subjects measure ("no analogy", "distant problem solving analogy", and "other analogy").

Two prior solution reference points were employed: (1) minimum distance from prior 5 concepts, and (2) distance from the just-prior concept. The two reference points provide complementary views of the designers' patterns of ideation search. The first reference point provided a stricter measure of jumps through the ideation space, since a given concept would have a high "distance from reference point" value if and only if it was substantially functionally different from all of the 5 solutions that immediately preceded it. The second reference point provided a more circumscribed measure of jumps, since a concept could have a high "distance from reference point" value if it was substantially functionally different from the solution that immediately preceded it, but functionally similar to the concepts prior to that one. For example, suppose the designers generated 5 concepts consecutively (C_1, C_2, C_3, C_4, and C_5). C_5 would receive a high "distance from reference point" value if it was substantially different from C_4, even if it was functionally similar to C_1, C_2, and C_3.

To thoroughly explore the space of possibilities for the effects of analogy, the "analogy before" measure was created at 3 different time windows: 5 lines, 10 lines, and 20 lines prior to the solution onset. Number of lines rather than time *per se* was chosen as the segmentation unit of analysis because the focus was on information exchange and cognitive processes, which could happen at varying rates with respect to the passage of time per se. This range of time window sizes reflected our focus on relatively immediate effects of analogy on ideation.

The process of creating the "analogy before" measure for each of the time windows was identical and was as follows. For each concept, its initial onset in the transcript was identified. Next, the lines (either 5, 10, or 20, depending on time window setting) prior to the onset were scanned to determine whether any of those lines contained at least part of an analogy/analogies, keeping separate track of *distance* and *purpose* of these analogy/analogies. With this information, each concept was classified as one of three groups: "no analogy", "distant problem solving analogy", and "other analogy", where "distant problem solving analogies" included all analogies that were both distant *and* either coded as concept generation or function-finding. The number of concepts in each "analogy before" level by time window and reference point are shown in Table 9.

Table 9. Number of concepts in each "analogy before" condition by time window and reference point type

	Min distance from last 5			Distance from just prior		
	No analogy	Distant problem solving analogy	Other analogy	No analogy	Distant problem solving analogy	Other analogy
Last 5 lines	73	24	6	95	30	10
Last 10 lines	59	33	11	80	38	17
Last 20 lines	45	39	19	63	45	27

The reason for singling out distant concept generation or function-finding analogies was twofold: (1) to reduce noise from analogies not expected to contribute directly to concept generation (i.e., explanation and problem identification analogies), and (2) to provide a stronger test of Hypothesis 1a, since the literature provides stronger support for the hypothesis that distant analogies would support jumps. It should be noted that, given the varying time window sizes, some concepts were preceded by multiple analogies. In these cases, the concept in question was assigned to conditions based on the predominant distance and purpose of the analogies; more specifically, a solution was assigned to the "distant solution generating analogy" condition if and only if the majority of the analogies (i.e., more than half) were distant *and* either concept-generating or function-finding.

2.3 RESULTS

Separate ANOVAs were run for the two "distance from reference point" dependent measure types for each of the time window sizes. Descriptive statistics for each reference point and time window combination are shown in Table 10.

Table 10. Descriptive statistics for distance from reference point measures by "analogy before" condition and time window

	Min distance from last 5			Distance from just prior		
	No analogy	Distant problem solving analogy	Other analogy	No analogy	Distant problem solving analogy	Other analogy
Last 5						
Mean	2.0	2.2	2.0	3.1	2.7	3.1
SE	*0.1*	*0.3*	*0.4*	*0.1*	*0.2*	*0.4*
Last 10						
Mean	2.1	2.1	1.3	3.3	2.6	2.8
SE	*0.2*	*0.2*	*0.3*	*0.2*	*0.2*	*0.3*
Last 20						
Mean	2.1	2.1	2.0	3.2	2.9	2.9
SE	*0.2*	*0.2*	*0.3*	*0.2*	*0.2*	*0.3*

Overall, no ANOVAs found a significant positive effect of distant solution generating analogies on either dependent measure. First, the ANOVAs on "minimum distance from last 5" showed no reliable effect of the "analogy before" measure at either the 5 line window, $F (2, 100) = .10$, $p = .91$, the 10 line window, $F (2, 100) = .53$, $p = .60$, or the 20 line time window, F (2,

100) = .06, p = .95. With respect to the "distance from just prior" measure, the ANOVAs showed no reliable effect at either the 5 line window, F (2, 132) = 1.29, p = .28, or the 20 line window, F (2, 132) = .64, p = .53. In contrast, the ANOVA for the 10 line window showed a reliable effect of the "analogy before" measure on "distance from just prior", F (2, 132) = 6.140, p = .03, η^2 = .051. However, the nature of the effect was contrary to the initial hypothesis; concepts following distant problem solving analogies tended to be significantly *less* distant from their immediate predecessors in comparison to baseline conditions (no analogy before), Cohen's d = -0.51 (95% confidence interval = -0.22 to -0.91) p = .03 (Bonferroni corrections for multiple comparisons). Post-hoc pairwise contrasts showed that only solutions following distant problem solving analogies differed significantly from baseline (no analogy before).

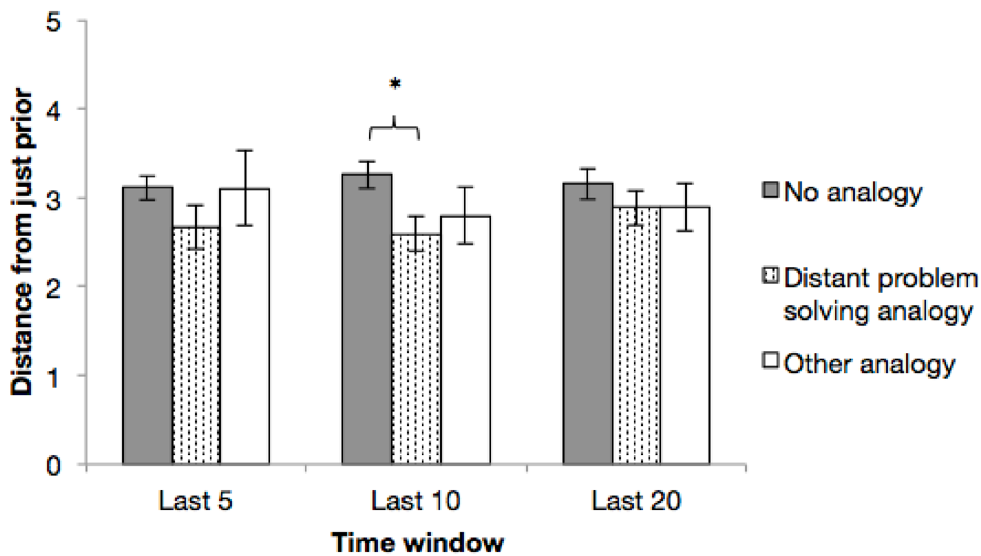

Figure 1. Distance from just prior by "analogy before" condition and time window. * denotes a statistically significant contrast at $p < .05$.

While the ANOVAs for the other time window sizes were not significant, Figure 1 shows that the mean trends in the 5-line window were in the same direction, i.e., *less* distance from just prior following distant problem solving analogies vs. baseline. The trend was similar but considerably muted in the 20-line window.

Figure 2 shows the frequency distribution of concepts at 5 functional distance cut-off points (using mean distance for each concept across raters), with the concepts at each cut-off point divided into three groups: (1) new concepts (in white) not preceded in the last 10 lines by any analogy, (2) new concepts (in light gray) preceded in the last 10 lines by analogies other than distant problem solving analogies, and (3) new concepts (in dark gray) preceded in the last 10 lines by distant problem solving analogies.

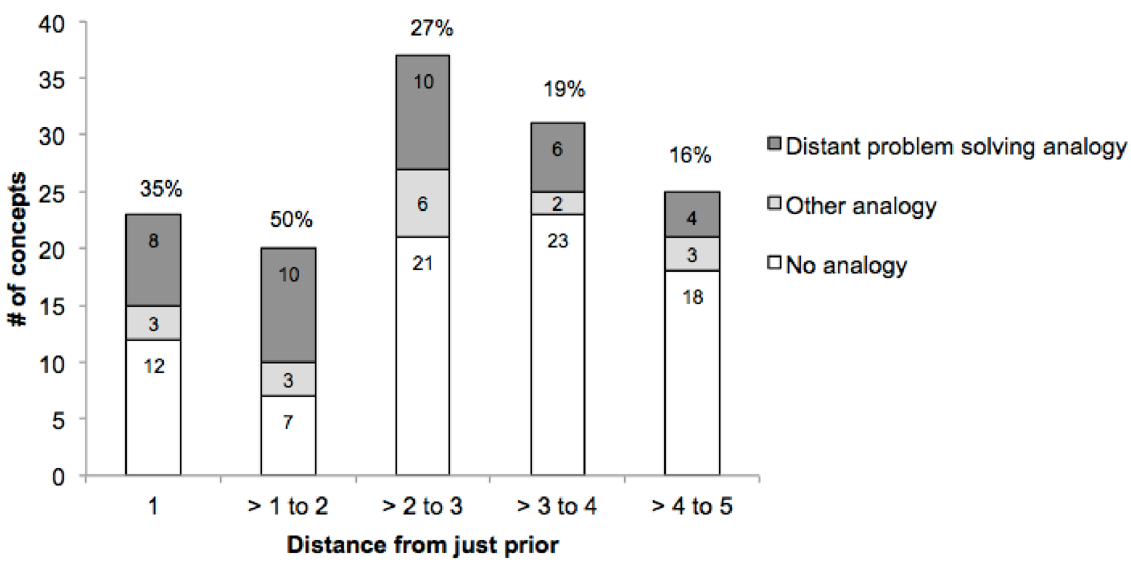

Figure 2. Frequency distribution of concepts at 5 functional distance cut-off points. Percentage values on top of each column denote the proportion of concepts at that cut-off point associated with distant problem solving analogies.

Four insights can be gleaned from inspecting this frequency distribution. First, attending to the overall summed bars, we can see that jumps are fairly common overall. Second, attending to the white bars alone, we can see that jumps are the most common search step when concepts closely associated with analogies in time are ignored. Third, focusing only on the concepts preceded by distant problem solving analogies (dark gray), incremental steps are almost twice as common as jumps (18 concepts with distance < 2 vs. 10 concepts with distance > 3). Finally, attending to the percentage values on each bar, we can see that distant problem solving analogies disproportionately account for most incremental steps (35% and 50% of concepts at the first two cut-off points) and relatively few jumps (19% and 16% of concepts at the last two cut-off points).

2.4 DISCUSSION

Overall, the results of the analysis in this study were two-fold: (1) rather than being associated with larger steps in the design concept space (mental jumps), analogies tended to be associated with more incremental moves, and (2) this effect of analogy appeared to be circumscribed in a relatively tight temporal boundary, i.e., distant problem solving analogies recently considered (in the last 10 lines) appear to lead to more continuous search vs. baseline conditions.

There are at least two explanations for this counter-hypothesis set of findings. First, analogies might have had an overall fixating effect on ideation, suppressing not just novel concepts but concept generation in general. There are two related notions of fixation in the design and creativity literature: one notion has to do with an inability to generate concepts that are significantly different from ones already considered (Jansson & Smith, 1991; Smith, Ward, &

Schumacher, 1993); another notion involves difficulty generating any concept at all, a sort of inverse of ideational fluency, an important and frequently measured component of creative thought (Guilford, 1950; Hennessey & Amabile, 2010; Runco, 2004; Shah et al., 2003). The inverse forms of these two kinds of fixations – being able to generate very different ideas, and ideational fluency – are often correlated, suggesting that they may be components of a more encompassing fixation effect. For example, the fluent generation of numerous concepts has been empirically associated with an increased probability of finding exceptional concepts (Guilford, 1950; Hennessey & Amabile, 2010; Runco, 2004; Shah, Vargas-Hernandez, & Smith, 2003). Also, increased feature transfer from examples during ideation has been associated with decreased levels of fluency (Chan et al., 2011). In light of this compound notion of fixation, if analogy use in the current dataset was associated with both kinds of fixation, there would be more support for an interpretation of Study 1's results in terms of an aggregate fixation effect.

On the other hand, if analogy use was associated with decreased functional distance only, but not decreased fluency, then a different inference might be drawn; it could be argued that analogy does not necessarily fixate *per se*, but rather is employed as a means of incrementally exploring promising regions of the design space. That is, rather than serving as "jumping points" into new regions of the solution space, analogies might be employed as a means of exploring currently considered regions of the space. Study 2 was conducted to generate evidence to decide between these alternative explanations.

3.0 STUDY 2

3.1 OVERVIEW

Study 2 examined whether analogy use was associated with a lower rate of concept generation relative to baseline levels. To address this question, a time-lagged logistic regression was employed; time-lagged, because this analysis would estimate the change in concept generation at time t and $t+1$ based on patterns of analogy use at time t, and logistic because the outcome variable was binary (i.e., did a designer generate a concept or not). This analysis assumed that (1) there was some baseline probability of a concept being generated in a given time slice, and (2) a decrease in this probability as a function of the presence of an analogy in the current or previous time slice would suggest that analogies were a significant source of fixation for these designers.

3.2 METHODS

3.2.1 Creating blocks.

The first step in the analysis was to segment the transcript into blocks for the time-lagged analysis. Given the indications from Study 1 that the effects of analogy use on ideation in this dataset were circumscribed to approximately within 10 lines of an analogy, block sizes of 5-lines and 10-lines were used to explore the space of possible analogy effects. The block creation process was the same for each of these block sizes, and was as follows. First, a coherent cluster of analogy utterances was identified and marked as its own block (recall that analogies could span multiple lines). Next, the *n* (5 or 10) lines before and after each analogy block were segmented into two additional blocks (see Figure 3).

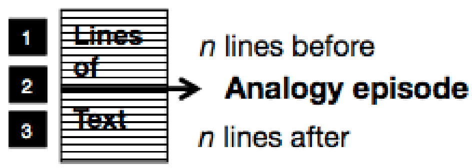

Figure 3. Analogy-centered block creation strategy

The rest of the transcript was broken up into successive n-line blocks, each ending at the n^{th} line, or with the next analogy block. This block creation strategy resulted in 157 analogy blocks and 801 non-analogy 5-line blocks, 428 non-analogy 10-line blocks. The reason for the discrepancy between the number of analogy blocks and the number of unique analogies identified in the transcript is that analogies sometimes re-entered the conversation at later times. Analogy block lengths ranged from 1 line to 28 lines (M = 5.1, SD = 4.7), with most (88%) analogy blocks being 10 lines or less.

Analogy onsets and offsets were used as boundary markers for blocks because the focus is on providing an estimate of the effects of analogy, which should be most directly shown when closely time-locked to analogies.

3.2.2 Measures and model parameters.

Separate one-predictor time-lagged logistic regression models, with “analogy now” (yes/no) as the predictor and “solution onset next” (yes/no) as the outcome variable, were run on the 5-line, 10-line, and 20-line block sets; for each block size setting, separate models were run with lags of 0 and 1 were selected, such that analogy use (present/absent) in one block predicted (1) the generation of a concept in the current block (lag 0), and (2) the generation of a concept in the subsequent block (lag 1). Using only lags 0 and 1 focuses on immediate consequences that best fits the hypotheses under test, and reduces the probability of finding spurious correlations from examining multiple lags.

The analogy measure was a binary variable measuring whether or not any concept generation or function finding analogy was present in the block (yes or no). Problem identification and explanation analogies were excluded because these analogies were not expected to contribute directly to solution generation. The concept generation measure was also a binary variable measuring whether or not a new concept onset was present in the block (yes or no); that is, a block was coded as “solution = yes” if and only if it contained an *onset* of a concept that was not mentioned in previous blocks. This ensured that the analysis would more cleanly reflect effects of analogies on the *generation* (vs. elaboration) of concepts. Similar to Study 1, concept generation rates associated with analogy were not compared with a traditional baseline, but rather with conditions in which cognitive processes other than analogy were being employed.

3.3 RESULTS

The odds ratios for each model block size setting and lag are summarized in Table 11. The models for the 10-line blocks did not show statistically reliable decreases in concept generation as a function of analogy use for either lag 0 or lag 1 relative to "baseline. For the 10-line blocks, the overall lag 0 model was not significant, χ^2 (1, N = 585) = .16, p = .70, Negelkerke R^2 = .000, and the analogy coefficient, β = 0.10, odds ratio = 1.10, was also not significant, Wald χ^2 (1) = .85, p = .36. The overall lag 1 model was also not significant, χ^2 (1, N = 585) = 1.24, p = .27, Negelkerke R^2 = .003, and the analogy coefficient, β = 0.26, odds ratio = 1.30, was not significant, Wald χ^2 (1) = 1.26, p = .26.

Table 11. Odds ratios by block size and lag type

Block size	Lag 0	Lag 1
10	1.10	1.30
5	2.09**	1.87*

Note: ** denotes $p < .01$; * denotes $p < .05$

The models for the 5-line blocks also did not show statistically reliable decreases in concept generation as a function of analogy use for either lag; on the contrary, analogy use was reliably associated with an *increase* in concept generation rate relative to baseline conditions, i.e., when designers were engaging in processes other than analogy. For lag 0, the overall model was significant, χ^2 (1, N = 403) = 9.14, p = .00, Negelkerke R^2 = .015, and the analogy coefficient, β = 0.74, odds ratio = 2.09, indicated that analogy use was associated with an approximately 110% increase in the odds of a concept being generated in the same block, relative to other processes the designer might otherwise be engaged in. This coefficient was significant, Wald χ^2 (1) = 9.85, p = .00. Similarly, for lag 1, the overall model was significant, χ^2 (1, N = 403) = 6.41, p = .01, Negelkerke R^2 = .011, and the analogy coefficient, β = 0.63, odds ratio = 1.87, indicated that analogy use was associated with an approximately 87% increase in the odds of a concept being generated in the next block, relative to other processes the designer might otherwise be engaged in. This coefficient was significant, Wald χ^2 (1) = 6.87, p = .01.

3.4 DISCUSSION

Taken together, the results of the models provided no support for the hypothesis that distant-concept-generating and function-finding analogies decrease fluency of ideation. On the contrary, the odds ratios from both the 10-line and 5-line block models were in a positive direction, and the coefficients in the 5-line models were significant. Thus, rather than decreasing fluency of ideation, the use of distant, concept generating and function-finding analogies appeared to support increased rates of concept generation, even when compared to other processes the designers might have been engaged in. These results do not support an interpretation of Study 1's results in terms of aggregate fixating effects on ideation, and instead support an interpretation in terms of analogy supporting exploration of potentially promising but already visited regions of the design space.

4.0 GENERAL DISCUSSION

4.1 SUMMARY OF FINDINGS

In summary, two studies were conducted to unpack in detail the effects of analogy use on ideation search patterns in the naturalistic conversations of a real-world professional design team. Study 1 showed that the use of analogy, specifically distant concept generating and function-finding analogies, was not associated with increased functional distance of proposed concepts from their predecessors. In fact, there was converging evidence that analogy use was temporally associated with *decreased* functional distance of search. Study 2 further tested whether analogies in this dataset had an overall fixating effect or whether the analogies were primarily used as operators for exploring previously visited regions of the design space. The results showed that analogy did not have a fixating effect. Thus, combining the results of Studies 1 and 2 suggests that analogy, even when analogical distance is high, is primarily associated with incremental traversal of the design space.

To illustrate the nature of these effects, I present two examples. In Table 12, the designers are searching for ways to protect the print head from being damaged by unexpected contact when the device is not printing, exploring a space of possible retractable covers for the print head. Two analogies are employed to generate two distinct variations on this solution approach: Concept 61 involves a mechanism similar to a video tape flap with a rigid flap that opens to release the print head for use, while Concept 62 involves a mechanism similar to a rolling garage door. The connection between these solution concepts and the analogies that generated them should be clear, as should be the relatively high degree of functional similarity between the two solution concepts.

Table 12. Example progression in solution exploration involving analogy

Analogy: Video tape flap		
1516	Todd	I'm thinking of something a bit like erm the flap on a video tape
1517		*(pause)*
1518	Alan	uh-huh what the flap?
1519	Todd	yeah
Analogy: Garage door		
1520	Tommy	like a garage door type of thing
Concept 61		
1521	Todd	yeah push the button
1522		then it goes open
1523	Tommy	yeah
1524	Todd	but that's probably overly complicated
Concept 61		
1525	Rodney	garage door well it could be a roller
1526	Todd	a roller door

In Table 13, the designers are searching for solutions to the problem of maintaining the optimal angle of contact between the print head and the media, given that the target users are young children who are unlikely to hold the printing device still to achieve that angle of contact without some help.

Table 13. Another example progression in solution exploration involving analogy

Concept 24		
693	Alan	so the design and shape of the thing so it can only be done in one way
693		and that's the correct way
694		because then there is less sort of learning to be done by the user
Concept 25		
729	Alan	you could even have some sort of feedback
730		in terms of colour LEDs on the pen saying that he's done a good job or she's done a good job or-
Analogy: DIY laser levellers		
729	Alan	because the other thing that you use to make sure things are level that's come out in the sort of DIY world is these laser levelers and things like that
Concept 28[1]		
779	Alan	if you had like a little laser that made sure it was level of some sort
780		erm you know the child can actually see a line
781		and that its at the right angle then
782		because they can see that the line is right
783		and then that would work-

The designer proposes Concept 24, which involves designing the shape of the device such that it forces the user to hold it in the "correct" way (i.e., in a way that preserves the optimum angle of contact between the print head and the media). Again, as in Table 12, the analogy was a direct source of Concept 28, which advanced the search in the design space incrementally by changing the way the feedback would be provided to the user, while retaining key functional features from Concept 25. Together, these extracts illustrate how analogy was a

[1] Solutions were actually sequential in the sub-problem space, but numbering is not sequential because solutions to other sub-problems were discussed in between solution 25 and the analogy

significant source of concepts, which tended to be incremental explorations in the design space, rather than large functional jumps.

4.2 CAVEATS

Some caveats should be mentioned before discussing the broader implications of this work. First, the present experimental approach involved a tradeoff between external and internal validity. While the naturalistic character of the data and the fact that the designers are real-world professionals lends external validity to the findings, it should be noted that the findings are correlational in nature, and tight experimental control of potential confounding variables was not possible. A related caveat has to do with the tradeoff between depth and breadth; the data collection, coding and analytic methods employed in the present work, while affording highly detailed looks at the temporal interplay between analogy use and ideation processes, are highly resource intensive, making comparisons across multiple expert datasets difficult. From one perspective, the sample size of the two studies was essentially $N = 1$, given that only one team comprised the totality of the data studied. For this reason, the present findings should be replicated with similar studies of other design teams before any strong conclusions can be drawn or generalized. Nevertheless, the high external validity of the data does provide some initial confidence that the findings will be robust across different design teams in similar creative situations.

Finally, the analogies in this dataset were primarily self-generated; that is, with just a few exceptions, most of the analogies were retrieved from the designers' memories. The few analogies that might have been retrieved from external sources were those generated prior to the first meeting; a meeting brief was sent around to the team prior to the first meeting, advising the designers of the major issues to be discussed in the two meetings (e.g., the angle problem, protecting the print head), and instructing the team members to bring to the meeting products or designs that have to glide smoothly over contours, to help kick-start ideation for the angle problem. The primarily self-generated character of the analogies stands in contrast to the externally given analogies in many of the prior studies of analogy in design. In light of this, one possible explanation for the continuous character of ideation search supported by analogy might be that many of the analogies were insufficiently distant from previously considered concepts, perhaps due to the constraints of human memory retrieval; one of the most robust findings on analogical retrieval from memory is that it is often driven by surface similarity (for reviews, see Forbus, Gentner, & Law, 1994; Hummel & Holyoak, 1997).

However, the vast majority of analogies in this dataset (84%) were distant, i.e., drawn from domains other than graphical production and printing devices. This accords with the arguments and data of researchers who have argued that, notwithstanding human memory's preferences for surface similarity during retrieval, individuals in naturalistic situations are able to prolifically retrieve analogies from memory based on deep structural similarity (Blanchette & Dunbar, 2000; Dunbar, 2001). Nevertheless, the present findings raise interesting questions about whether the characteristics of human memory constrain the range of *functional* distance of analogies retrieved from memory. That is, it is possible that, given the computational constraints of analogy (e.g., preferring systematic matches, one-to-one mappings; Gentner, 1983) and the associative character of memory, designers might not be able to retrieve from memory other concepts that solve similar sub-problems in very different ways, especially if these concepts are embedded within designs or products with very different overall functionality. Different effects of analogy on ideation search patterns might be observed with externally-provided analogous sources that are highly distant functionally.

4.3 IMPLICATIONS AND FUTURE DIRECTIONS

Overall, the current data support a characterization of (self-generated) analogy as primarily an incremental search operator during creative ideation. Combining these findings with the large body of evidence linking analogy to creative outcomes suggests that a major route via analogies to innovative concepts runs through an accumulation of incremental development of concepts, much like the process described by Dunbar (1997) and Weisberg (2009). This characterization of creative ideation does not necessarily rule out the occurrence of creative jumps in ideation spaces; it merely elevates the importance of fluency of ideation and incremental development of concepts.

However, jumps may sometimes be necessary. Perkins (1994) has described a potential "isolation problem" in creative problem spaces, where innovative solutions are bounded in the space by wildernesses of no promise. In these situations, incremental search may lead to an impasse, since there is no incremental path into the location of the innovative solution that avoids going through highly unpromising options. It may be that large jumps into these isolated regions of promise might be facilitated by highly functionally distant analogies, perhaps sparked by external stimulations. This notion is supported by the literature on incubation and "prepared mind" effects, where creative problem solvers overcome impasses in their problem solving by unexpectedly encountering potentially relevant ideas in their environment after having set their problem aside (Christensen & Schunn, 2005; Seifert et al., 1995; Tseng et al., 2008). These ideas suggest that impasses may be a prerequisite for observing jumps supported by analogy. Given that impasses were not observed in the current data, it may be premature to conclude that analogies *in general* do not function as jump operators.

Together, these observations in tandem with the current findings suggest a more refined resolution of the conflicting views of analogy as primarily supporting jumps or incremental search. It may be that analogies retrieved from memory serve as “workhorses” that enable designers and other creative problem solvers to incrementally traverse their problem spaces, and that externally provided analogies enable jumps out of local maxima in impasse situations.

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