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The Impact of Analogies on Creative Concept Generation: Lessons From an *In Vivo* Study in Engineering Design

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Abstract

Research on innovation often highlights analogies from sources outside the current problem domain as a major source of novel concepts; however, the mechanisms underlying this relationship are not well understood. We analyzed the temporal interplay between far analogy use and creative concept generation in a professional design team's brainstorming conversations, investigating the hypothesis that far analogies lead directly to very novel concepts via large steps in conceptual spaces (jumps). Surprisingly, we found that concepts were more similar to their preceding concepts after far analogy use compared to baseline situations (i.e., without far analogy use). Yet far analogies increased the team's concept generation rate compared to baseline conditions. Overall, these results challenge the view that far analogies primarily lead to novel concepts via jumps in conceptual spaces and suggest alternative pathways from far analogies to novel concepts (e.g., iterative, deep exploration within a functional space).

Keywords: Analogy; Creativity; Design cognition; Problem solving; *In vivo*

1. Introduction

Innovation is a key output of human cognition and therefore an important object of study for cognitive science. Arguably, the ability to produce novel artifacts that solve some problem and bring significant value to stakeholders/society is comparable to other great human intellectual achievements, such as great art, literature, and achieving detailed understanding of the natural world through the scientific method. Consider the LIFE-SAVER® portable filtration system, a durable, inexpensive, and portable means of turning dirty and pathogen-ridden water into clean, life-saving drinkable water in seconds

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(Walters, 2013). It represents a viable solution to the extensive problem of water poverty, sidestepping the major obstacle of infrastructure modification difficulties; in fact, it is already transforming the lives of thousands of people in rural Borneo. How do innovations like this arise from human minds and their interactions with their surroundings?

From both a practical and a theoretical standpoint, the mental representations and processes that lead to innovation are a worthy topic of inquiry for cognitive science; practically, because of innovation's cultural and economic importance, and theoretically, because by virtue of its complex, multifaceted nature, it can serve as a test bed for theories of cognition. In decades of cognitive-based research on the topic of innovation, 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), external representations (Goel, 1995), and mental simulation (Ball & Christensen, 2009; Christensen & Schunn, 2009b), among others. Fundamental to innovation, however, is concept generation. One cannot "make a silk purse out of a sow's ear" (Kornish & Ulrich, 2014); execution and implementation are critical, but innovation ultimately begins with good concepts. More specifically, as some theorists would argue, "breakthrough" or "radical" innovation comes from good concepts that are also very *new* (Boden, 2004).

The present work focuses on analogy, a cognitive process that has been hypothesized to be a major source of new concepts. 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 (French, 2002; Gentner, 1983; Gentner & Forbus, 2011; Holyoak & Thagard, 1996; Hummel & Holyoak, 1997). 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). This process appears to be important for generating novel concepts in a wide variety of domains, perhaps most prominently in scientific discovery (Clement, 1988; Dunbar, 1997; Gentner et al., 1997; Holyoak & Thagard, 1996; Nersessian, 1992; Oppenheimer, 1956) and—the domain of focus in this article—technological invention and innovation. In technological innovation, analogies have been associated with innovative outcomes in protocol studies and retrospective studies of expert and prominent inventors and designers (Carlson & Gorman, 1990; Gorman, 1997), experimental studies of design processes (Chan et al., 2011; Dahl & Moreau, 2002; Goldschmidt, 2001; Vargas-Hernandez, Shah, & Smith, 2010), and computational models of design (Gero & Kazakov, 1998). Analogy is also an important component of formal innovative design methods, such as design-by-analogy (French, 1988; Gordon, 1961; Hacco & Shu, 2002; Hey, Linsey, Agogino, & Wood, 2008; Linsey, Murphy, Laux, Markman, & Wood, 2009).

Not all analogies are thought to be equally productive for creative outcomes. Many theorists argue that, when considering the analogical distance of sources, far analogies—that is, from sources that have a low degree of overlap of surface elements with the current problem domain—hold the most potential for generating very new concepts (Gentner

& Markman, 1997; Holyoak & Thagard, 1996; Poze, 1983; Ward, 1998). A number of studies have shown that using or being stimulated by far analogies can increase production of very new concepts relative to near or no analogies (Chan et al., 2011; Chiu & Shu, 2012; Dahl & Moreau, 2002; Gonçalves, Cardoso, & Badke-Schaub, 2013; Hender, Dean, Rodgers, & Jay, 2002), although some studies have not replicated this finding (Huh & Kim, 2012; Malaga, 2000; Wilson, Rosen, Nelson, & Yen, 2010).

How might far analogies lead to very novel concepts? One prominent hypothesis, borrowing from the theoretical characterization of creative concept generation as search in a space (Boden, 2004; Goel & Pirolli, 1992; Perkins, 1994, 1997; Simon, 1996), is that far analogies enable "jumps" in the space of possible concepts. In other words, in contrast to more incremental search strategies, such as hill climbing, using far analogies enables the creator to "jump" to concepts that are very different from the set of concepts currently considered. The early roots of this notion can be found in Koestler's (1964) "bisociation" theory of creativity, where he argues that the best concepts come from when two previously unrelated concepts are combined into a new concept that is highly original and different form current concepts. Mednick's (1962) associative theory of creativity advances a similar argument about far connections enabling jumps in associative space to a highly creative concept. More recently, Perkins (1994, 1997) outlined the "canyon" problem as a topographical challenge of search spaces for problems requiring innovation, where the crucial insight may lie in a very distant part of the space, isolated from one's current location; importantly, he suggests that "analogy inherently has the power to step across canyons by relating one domain to another" (Perkins, 1997, p. 534). The idea that crucial insights may lie outside one's domain is consistent with the rise of collaborations and interdisciplinarity in science and technology (Jones, 2009; Paletz & Schunn, 2010; Wuchty, Jones, & Uzzi, 2007). Social network theories of innovation also emphasize the privileged position of agents positioned in "structural holes" in the information network (Burt, 2004; Hargadon, 2002; Ruef, 2002; Tortoriello & Krackhardt, 2010), being able to bridge knowledge and resources from structurally separated regions of the network.

While this hypothesis about the relationship between far analogies and creative concept generation (i.e., far analogies lead to very novel concepts via "jumps" in conceptual space) seems plausible and theoretically motivated, there is a critical empirical gap; online studies of concept generation have not measured and analyzed far analogy use and conceptual search patterns together. Prior studies showing a positive effect of far analogies on novelty of generated concepts have typically done so in an "input-output" design, where the conceptual *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 far analogies and generated concepts to incrementally arrive at novel concepts in a way that is not recorded in their final recorded designs. Retrospective interviews of prominent innovators are of little help; potential issues surrounding incompleteness, inaccuracy, and bias in retrospective reports are well documented (for a review, see Schacter, 1999) and may be exacerbated when one is asked to retrospect for a phenomenon about which one has (lay) theories, as may often be the case in creativity research (Perkins, 1981). This lack of detailed examinations of the interplay between far analogies and concept generation is a major obstacle to theoretical progress in understanding the precise ways in which analogies can impact creative concept generation. Taking an *in vivo* approach, we address this gap by presenting detailed analyses of the online interplay between far analogies and concept generation in a team of real-world professional designers.

2. Study 1

2.1. Overview

This study presents analyses of multiple hours of naturalistic brainstorming conversations of a real-world professional design team, involving a large number of analogies and diverse set of subproblems. The design team consisted of 10 professionals from a range of design-related disciplines, including electronics and business development, mechanical engineering, business consulting, ergonomics and usability, and industrial design and project management. The team was tasked with developing a new product concept for a hand-held application of thermal printing technology for children. Within a larger taxonomy of design problems, ranging from routine (e.g., configuration/parametric design) to non-routine (creating original products), where non-routine problems are perceived as requiring more innovation (Chakrabarti, 2006; Dym, 1994; Gero, 2000), this problem is clearly non-routine, with the goal being to design a completely novel product in a new market, albeit leveraging an existing core technology. Thus, this design context is well suited for observation of processes that might lead to more “radical” rather than “incremental” innovation, where radical innovation has been more closely identified as coming from very novel concepts (Dewar & Dutton, 1986).

These conversations unfolded over the course of two design team meetings, structured as “brainstorms,” with a focus on concept generation; the first meeting lasted 1 h and 37 min and focused on mechanical design subproblems; the second meeting lasted 1 h and 40 min and focused on electronics subproblems. The meetings were recorded with four pre-placed cameras in the meeting room. Although no researcher was present at either meeting, the designers were aware that they were being recorded, and that the data would be used, along with recordings of design meetings at other companies, for a large study by the Open University on “design meetings in practice.” The transcripts include humor and outlandish statements, suggesting they were not very inhibited by the presence of cameras.

Prior to the first meeting, the designers received a design brief that requested that they think about problems related to the print head mounting design and pen format (e.g., keeping the print head level in spite of users’ wobbly arm movement, protecting the print head from overheating and impact damage). To stimulate concept generation for these problems, the designers were also asked to bring along products (or pictures of products) that glide smoothly over contours.

The purpose of Study 1 was to determine whether far analogies were associated with conceptual jumps during concept generation. We operationalized jumps in terms of functional distance, that is, the degree to which a given concept's described functionality (i.e., a way of satisfying some design requirement vs. changes in color or manufacturing material not directly tied to changed functionality) was different from a prior concept or set of concepts. This operationalization reflects our focus on "radical" innovation, which in engineering and technological contexts has been associated with changes in functionality; for instance, Sood and Tellis (2005) argue that "platform innovation"—new functionality based on novel working/scientific principles (e.g., from magnetism for reading/writing data with floppy disks to laser optics for compact disks)—is where "breakthrough" or "radical" innovation happens. With this operationalization, the working hypothesis to be tested in Study 1 was the following: *The functional distance of a proposed concept from concepts recently considered will be reliably greater when preceded by far analogies versus baseline, that is, when not preceded by far analogies.*

Some discussion of validity and reliability is required given the deviations from a typical laboratory study along several dimensions. First, the data are narrow in the sense of studying one team and only 10 individuals working on one larger design problem. But the team worked on many different functional problems and generated a large number of different analogies; thus, this dataset is broader in another sense than a typical laboratory study that often examines the effect of one or two provided analogies on one given problem. Second, in terms of generalizability, it is not obvious that studying 100 undergraduates with low prior knowledge in the given domain, little relevant disciplinary training, and little incentive to do well produces outcomes of greater generalizability than the study of seven motivated, knowledgeable, and richly trained adults from diverse backgrounds working over multiple hours on many subproblems. Instead, it is likely that cognitive science will benefit from encouraging just as many studies of cognition in the wild as studies in the laboratory.

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 analogy use

Coding of analogy use was conducted by a prior research team, whose findings have been published in Ball and Christensen (2009); the second author, who has many years of expertise in studying analogy *in vivo*, served as the primary coder, with a secondary coder not affiliated with the research project recruited and trained to serve as a reliability check. 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. One Hundred and forty-four analogies were found across the two transcripts (79 in the first and 65 in the second), with all designers contributing analogies at approximately the same rate, commensurate with their level of participation in the meetings overall (correlation between number of analogy and non-analogy utterances across designers was high, $r = .72$). Inter-rater reliability, assessed by comparing the primary and secondary coder's codes for approximately 1 h worth of transcript, was acceptable, at (Cohen's kappa) $k = .77$. This method of assessing inter-rater reliability was also used for the remaining analogy codes.

Analogies were coded for both distance and purpose. Following previous *in vivo* studies of analogy (Ball & Christensen, 2009; Christensen & Schunn, 2007), analogies were coded near versus far as follows: *Near* analogies involved mappings from sources that related to tools, mechanisms, and processes associated with graphical production and printing, while *far* analogies involved mappings from more far sources (see Tables 1 and 2). Of the 144 analogies found, 16% were coded as near, and 84% were coded as far. Inter-rater reliability was very high, $k = .99$. Because near analogies were relatively rare and because they are not the focus of prior hypotheses regarding impacts on concept generation, the analyses focus on the effects of the far analogies.

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 three levels, with a fourth level added as a theoretical contribution by Ball and Christensen (2009; see Tables 3–6 for examples): (a) *Problem identification*—noticing a possible problem in the emerging design, where the problem was taken from an analogous source domain; (b) *Concept generation*—transferring possible design concepts from the source domain to the target domain; (c) *Explanation*—using a concept from the source domain to explain some aspect of the target domain to members of the design team; and (d) *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 also high, $k = .85$.

2.2.3. Coding concept generation

Because coding concept generation was more difficult, three coders, including the author and two trained research assistants, identified generated concepts and the subproblems they were intended to address. Similar to the coding of analogy use, concepts were

Table 1
Example of near analogy

976	Alan	the other thing 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
988		whereas in what we're looking at it could actually be as wide or wider-

Table 2
Example of far analogy

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

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

777	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 levellers and things like that
779		if you had like a little laser that made sure that 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

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

1161	Tod	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	Tod	exactly so you can make you can make the footprints-

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 solve some design subproblem, where a design subproblem was defined as either (a) something the device (or a subsystem 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 (b) something the device or subsystem 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 subproblem level provided external validity to the coding scheme, given the primary focus on concept generation, as concept generation in professional engineering practice routinely occurs following decomposition of an overall design problem into subproblems which are then addressed iteratively, sometimes in tandem (Ball, Evans, Dennis, & Ormerod, 1997; 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. Through exhaustive triple coding, identification of concepts utterances was done at a high level of reliability; the intra-class correlation coefficient across the three coders was .88 (90% raw agreement).

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 or more subproblems 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 subproblems were identified. Examples of subproblems 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 subproblem "keep the print head level." Due to the nature of the thermal printing technology, the thermal print head had to interface with the printing media within a strict range of angles in order for printing performance to be acceptable; however, the target market for the product concept, that is, young children between the ages of 5 and 7, was judged as particularly unlikely to hold pens and writing devices in stable ways. This subproblem was a major one discussed by the designers, and 35 distinct concepts were proposed for addressing it. The concept proposed in Table 7 was essentially a forcing function that would (via the

Table 7
Example of 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

shape of the device) force a particular way of holding the device that would insure appropriate angles of contact.

2.2.4. Constructing conceptual search spaces

To characterize the designers' search patterns during concept generation, it was necessary to first characterize the search spaces. As functional distance of concepts within the search space was the focus, a functional similarity space for concepts within each subproblem space was constructed via pairwise comparison ratings of functional distance for each concept in each subproblem space. That is, within each subproblem 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 subproblem. Two senior engineering undergraduate students (in mechanical and electrical engineering, respectively—both engineering subdisciplines highly relevant to the subproblems being solved by the designers) conducted the pairwise ratings of functional distance. These students were selected for their design experience and strong recommendations by engineering faculty with whom they had taken coursework.

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 non-trivial differences), 3 = *somewhat different* (some overlap, some differences), 4 = (little overlap, numerous differences), and 5 = *radically different* (very minimal/trivial overlap). Examples of 1 and 5 rated pairs are given in Table 8 (all concepts from the "keep the print head level" subproblem space).

The coding procedure was as follows. For each subproblem space, the two coders together first looked through the list of proposed concepts in the space and agreed upon an initial set of important points of contrast for comparing concepts. For example, for

Table 8
Example of concept pair ratings

Concept 1	Concept 2	Distance
No. 28: Laser mechanisms detect angle of contact and provide feedback to user	No. 29: Project multiple light points from device that converge when print head is at correct angle	1
No. 14: Device is toy with one or more wheels	No. 16: Put three ball bearings around print head to interface with media	1
No. 8: Use a different type of print head with more favorable angle tolerance	No. 86: Have a switch that controls print head action based on angular movement	5
No. 32: Add a dedicated feedback display that goes on user's wrist to give feedback on device angle	No. 84: Add disc around print head that restricts angle of contact with media	5

concepts proposed for the subproblem “keep the print head level,” one point of contrast was “user versus 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 subproblem 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.

It should be noted that not all concepts entered into the analysis. Because the current analysis was focused on movement within a conceptual space, subproblems with less than three proposed concepts were excluded. The final set of concepts for analysis included 135 proposed concepts for nine major subproblems (see Table 9). Inter-rater reliability for this measure was excellent, with an intra-class correlation coefficient of .94 for ratings in the final set of concepts.

2.2.5. Constructing independent and dependent variables

2.2.5.1. Dependent variables: The primary dependent variable was distance from prior concepts. Two prior concept reference points were employed: (a) MIN FROM LAST 5—minimum distance from the prior five concepts and (b) JUST PRIOR—distance from the JUST PRIOR concept. The two reference points provide complementary views of the designers' patterns of conceptual search: MIN FROM LAST 5 provided a stricter measure of jumps through the conceptual space, as a given concept would have a high “distance from reference point” value, if it was substantially functionally different from all of the five concepts that immediately preceded it; JUST PRIOR provided a more circumscribed measure of jumps but one that might capture more localized movement in the conceptual space. For example, suppose the designers generated five 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.

Although the ratings were technically obtained in an ordinal fashion, they are meant to approximate an interval scale, as is the case with the majority of Likert-type scales,

Table 9
Subproblems by number of concepts

Subproblem	No. 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
Insure print head only fires when on media	5
Maintain appropriate surface area of contact between print head and media	3

which are frequently analyzed with ANOVAS, and results are most often very consistent with complementary analyses using non-parametric models. More important, we have direct evidence from our data that our distance measure behaves in a way that approximates an interval scale; the ratings for the three largest subproblem spaces (i.e., "keep the print head level," "specific application concept of product," and "protect the print head") closely approximate the triangle inequality (i.e., for any triangle, the sum of the lengths of any two sides must be greater than the length of the remaining side), an important property that must hold for distances in Euclidean space (which are interval scale; Beals, Krantz, & Tversky, 1968). Less than 1% of the triangles in the first two subproblem spaces, and less than 4% of triangles in the remaining subproblem space violate this inequality (most violations consist of the remaining side being within one point of the sum of the other two sides). For these reasons, we analyze our dependent variables as interval scales.

2.2.5.2. Independent variables: The primary independent variable was an ANALOGY BEFORE measure, which had two levels: (a) FAR ANALOGY, for concepts preceded by analogies that were both far *and* concept generating (function-finding analogies were included in this definition, as they served the purpose of generating new functional elements for a concept) and (b) *baseline,* for concepts not preceded by any far analogies (as defined in [a]). To thoroughly explore the space of possibilities for the effects of analogy, ANALOGY BEFORE was created at two different time windows: 10 and 5 lines prior to the concept 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 far analogies on concept generation.

The process of creating ANALOGY BEFORE 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 *n* lines 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, concepts were classified into either the *baseline* or FAR ANALOGY groups; if a concept was preceded by an analogy that was not both far and concept generating, it was discarded. This allowed for a clean estimation of the effects of far concept-generating analogies on the conceptual search process. Hereafter, the term "far analogies" will be used as shorthand to refer to "far analogies used for concept generation." The number of concepts in each ANALOGY BEFORE level by reference point is shown in Table 10.

It should be noted that some concepts were preceded by multiple analogies. In these cases, the concept in question was classified based on the predominant distance and purpose of the analogies; more specifically, a concept was assigned to the FAR ANALOGY level if and only if the majority of the analogies (i.e., more than half) were far *and* either concept generating or function finding. In addition, given the naturalistic character of the data, the comparison to *baseline* is not to a standard "control" no input condition, but

Table 10
Number of concepts in each ANALOGY BEFORE condition at 10-line and 5-line windows at two different reference points for distance from prior concepts

	10-Line Window		5-Line Window	
Reference point	Baseline	FAR ANALOGY	Baseline	FAR ANALOGY
MIN FROM LAST 5	59	33	72	25
JUST PRIOR	81	38	95	30

Table 11
Mean (and standard error) functional distance for each ANALOGY BEFORE level at 10-line and 5-line windows, with two different reference points for distance from prior concepts

	10-line window		5-line window	
Reference point	Baseline	FAR ANALOGY	Baseline	FAR ANALOGY
MIN FROM LAST	2.1 (0.2)	2.0 (0.2)	2.1 (0.1)	1.9 (0.2)
JUST PRIOR	3.3 (0.2)	2.6 (0.2)	3.2 (0.1)	2.6 (0.2)

more precisely against functional distance of search when the designers were not using far analogies; other concept-generating strategies were more than likely being employed, such as reasoning from first principles and mutation of existing concepts (Gero & Maher, 1991; Ullman, 2002). That is, the study evaluates whether far analogies are particularly powerful, as the literature argues, rather than simply evaluating whether it has any effect at all.

2.3. Results

Four separate one-way ANOVAS were run for the two distance from reference point-dependent variables, two using MIN FROM LAST 5 as the dependent variable: (a) MIN FROM LAST 5 by ANALOGY BEFORE (10-line window) and (b) MIN FROM LAST 5 by ANALOGY BEFORE (5-line window); and two with JUST PRIOR as the dependent variable: (c) JUST PRIOR by ANALOGY BEFORE (10-line window) and (d) JUST PRIOR by ANALOGY BEFORE (5-line window). Distance from reference point means for each ANALOGY BEFORE level, for both 10-line and 5-line windows, are shown in Table 11.

2.3.1. MIN FROM LAST 5

2.3.1.1. 10-line window: There was no statistically significant main effect of ANALOGY BEFORE, $F(1, 95) = 0.36$, $p = .55$. Concepts were neither more nor less distant from their last five predecessors when preceded in the last 10 lines by far analogies versus baseline conditions, Cohen's $d = -0.06$ (95% confidence interval = −0.46 to 0.24).

2.3.1.2. 5-line window: There was no statistically significant main effect of ANALOGY BEFORE, $F(1, 90) = 0.08$, $p = .78$. Concepts were neither more nor less distant from their last five predecessors when preceded in the last five lines by far analogies versus baseline conditions, Cohen's $d = -0.14$ (95% confidence interval = -0.61 to 0.13).

2.3.2. *Just prior*

2.3.2.1. 10-line window: There was a statistically significant main effect of analogy before measure, $F(1, 117) = 6.47$, $p = .01$, $\eta^2 = .05$. However, the nature of the effect was contrary to the initial hypothesis; concepts were less distant from their immediate predecessors when preceded in the last 10 lines by far analogies versus baseline conditions, Cohen's $d = -0.50$ (95% confidence interval = -0.90 to -0.21).

2.3.2.2. 5-line window: There was a statistically significant main effect of analogy before, $F(1, 123) = 4.52$, $p = .04$, $\eta^2 = .04$. As with the 10-line window analysis, concepts were less functionally distant from their immediate predecessors when preceded in the last five lines by far analogies versus baseline conditions, Cohen's $d = -0.45$ (95% confidence interval = -0.90 to -0.18).

Fig. 1 illustrates the nature of the effect found in the anovas with just prior as the dependent variable. Each stacked bar presents percentage of concepts at each functional distance level in the two analogy before levels (defined at the 5-line window). Attending first to the *baseline* bar, it is clear that jumps (distance from just prior >3; the darker gray regions) are a common search step when designers were not using far analogies for concept generation, accounting for approximately half of all such concepts. Attending next to the far analogy bar, the contrast with the baseline concepts in terms of relative distributions of search steps is clear; far analogies are followed by more hops (distance from just prior ≤2; 50% of concepts) compared to baseline conditions (27% are hops). This pattern suggests that the biasing toward hops from immediate predecessors is not spurious (e.g., driven by a few outlier far analogy-concept cases), but rather may be indicative of a general pattern of far analogy's impact on creative concept generation, at least for these expert designers.

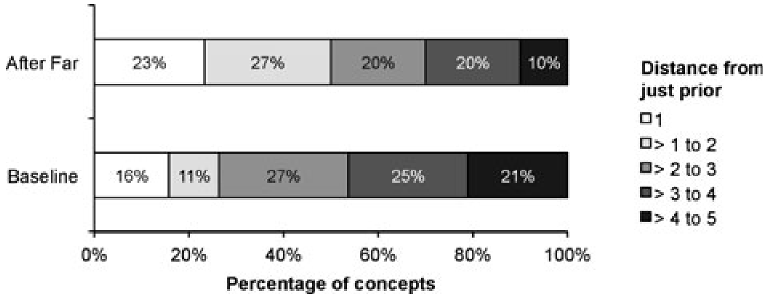

Fig. 1. Percentage of concepts at 5 distance from just prior cutoff points, presented for baseline and far analogy concepts, defined at the 5-line window.

2.4. Discussion

Overall, Study 1 found no support for the hypothesis that far analogies would lead to more jumps than hops, compared to baseline conditions; specifically, the analyses showed that the functional distance of proposed concepts from their immediate predecessors was *not* reliably greater when preceded by far analogies versus baseline. This result was robust across a range of time windows and measures. In fact, not only did functional distance from predecessors appear to be equivalent in the FAR ANALOGY versus *baseline* cases; when considering the distance of concepts from their immediate predecessors, FAR ANALOGY use was associated with conceptual moves that were *more* incremental than concept generation using other thought processes.

3. Study 2

Study 1's surprising counter-hypothesis findings raise questions surrounding the overall impact of far analogies on concept generation. The suppression effect on functional distance might be seen as evidence of fixation, in the sense of a decrease in the ability to generate concepts that are significantly different from ones already considered (Jansson & Smith, 1991; Smith, Ward, & Schumacher, 1993). This sort of fixation has been correlated with a decrease in the fluency of concept generation, another phenomenon that has been termed "fixation" due to the hypothesized importance of fluency for innovative outcomes (Guilford, 1950; Hennessey & Amabile, 2010; Runco, 2004; Shah, Vargas-Hernandez, & Smith, 2003; Terwiesch & Ulrich, 2009); for instance, increased fixation to example features during concept generation was associated with decreased levels of fluency (Chan et al., 2011), and the fluent generation of numerous concepts is empirically associated with the rate of generating novel, highly innovative concepts (Simonton, 1997). Thus, it is reasonable to ask whether the far analogies would also decrease fluency of concept generation.

Whether or not the far analogies decrease concept generation fluency has implications for the interpretation of Study 1's findings. If FAR ANALOGY use was associated with both suppressed functional distance of search *and* reduced concept generation fluency, it might be reasonable to suppose that the far analogies in this context were not productive (e.g., they were "fixating"). By contrast, if Study 2 did not yield evidence of suppression of concept generation fluency, Study 1's findings might be indicative not of the impact of unproductive far analogies but rather of a productive use of far analogies, focused on local idea exploration.

3.1. Overview

Given the *in vivo* and temporal nature of our data, we elected to examine the relationship between far analogies and concept generation fluency in terms of changes in the *probability* of generating concepts. Specifically, Study 2 examined whether FAR ANALOGY use was associated with a *lower* probability 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 probability at time t and $t + 1$ based on patterns of FAR 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 (a) there was some baseline probability of a concept being generated in a given time slice and (b) a decrease in this probability as a function of the presence of a FAR ANALOGY in the current or previous time slice would suggest that the far analogies were reducing fluency of concept generation.

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. As similar trends were seen with block sizes of 10 and 5 lines in Study 1, and concepts were less rare than analogies, we selected a block size of five lines for this analysis to achieve a more favorable tradeoff between time window precision (estimating more immediate effects of FAR ANALOGY) and noise due to attrition (smaller time window leads to more attrition of measured phenomena).

Sets of five consecutive lines were chunked to create separate blocks. When a coherent cluster of analogy utterances occurred that contained at least one far concept-generating analogy (here, as with Study 1, this included both concept generation and function-finding analogies), it was marked as its own block, beginning from the start to the end of the analogy cluster. Subsequent sets of five consecutive lines continued to be clustered into separate blocks, until the next cluster of FAR ANALOGY utterances began (see Fig. 2 for a visual summary of the block creation strategy). Analogy onsets and offsets were used as boundary markers for blocks because the focus is on estimating the effects of analogy, which should be most directly shown when closely time locked to analogies. Because of

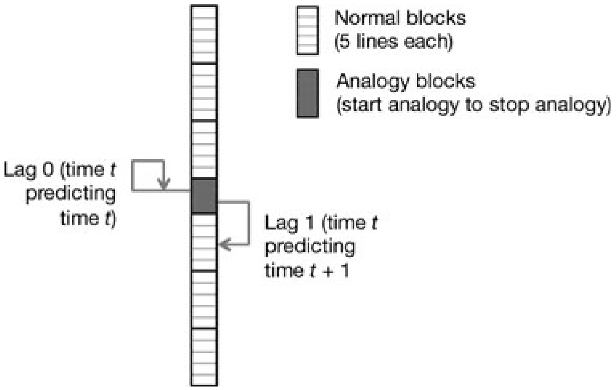

Fig. 2. Analogy-centered block creation strategy and time lags.

this analogy-centered block creation strategy, blocks immediately preceding analogy blocks were sometimes (fewer than 6% of blocks) less than five lines long.

This block creation strategy resulted in 97 analogy blocks and 843 non-analogy 5-line blocks. The reasons for the discrepancy between the number of analogy blocks and the number of unique analogies identified in the transcript (i.e., 147) are that (a) analogy clusters that did not contain far concept-generating analogies were treated as "normal" blocks, (b) analogies sometimes re-entered the conversation at later times, and (c) some analogy clusters were composed of more than one analogy (if they occurred in immediate succession). Analogy block lengths ranged from 1 line to 28 lines (*M* = 5.2, *SD* = 4.9), with most (88%) analogy blocks being 10 lines or less.

3.2.2. Independent and dependent variables

3.2.2.1. Independent variable: Similar to Study 1, the independent variable was FAR ANALOGY and had two levels: *yes*, if the block contained a FAR ANALOGY, and *no*, if it did not. Thus, as in Study 1, concept generation rates associated with far analogies were not compared with a traditional baseline, but rather with conditions in which other cognitive processes were being employed.

3.2.2.2. Dependent variable: The dependent variable, NEW CONCEPT, was a binary indicator for whether or not a NEW CONCEPT onset was present in the block (*yes* or *no*) regardless of functional distance to prior concepts; that is, a block was coded as "concept = 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 far analogies on the *generation* (rather than elaboration) of concepts.

3.3. Results

Two separate time-lagged logistic regression models were estimated for lag 0 and lag 1 relationships between the FAR ANALOGY and NEW CONCEPT measures. The lag 0 model estimated the co-occurrence relationship between FAR ANALOGY at time t and NEW CONCEPT at time t; the lag 1 model estimated the relationship between FAR ANALOGY at time t and NEW CONCEPT at time $t + 1$ (i.e., in the next block; see Fig. 2 for a visual depiction of each time lag). Using only lags 0 and 1 focuses on immediate consequences that best fit the hypotheses under test and reduce the probability of finding spurious correlations from examining multiple lags.

The odds ratios for each lag are summarized in Table 12. The models did not show any decrease in concept generation as a function of FAR ANALOGY for either lag (nor did analyses using larger or smaller window sizes); on the contrary, FAR ANALOGY use was reliably associated with an *increase* in concept generation rate relative to baseline conditions, that is, when designers were engaging in processes other than using far analogies to generate concepts. For lag 0, the overall model was statistically significant, χ^2 (1, $N = 938$) = 8.02, $p = .00$, Negelkerke $R^2 = .013$, and the coefficient for the FAR ANALOGY predictor, $\beta = .69$, odds ratio = 1.99, indicated that FAR ANALOGY use was associated with

Table 12
Odds ratios by lag type for logistic regressions of NEW CONCEPT on FAR ANALOGY

		95% CI	
	Odds ratio	Lower Limit	Upper Limit
Lag 0	1.99**	1.26	3.15
Lag 1	1.88**	1.18	2.98

Note. **Denotes $p < .01$.

an approximately 100% 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 statistically significant, Wald χ^2 (1) = 8.59, $p = .00$.

The lag 1 model estimates were very similar. The overall model was statistically significant, χ^2 (1, N = 938) = 6.63, p = .01, Negelkerke R^2 = .011, and the estimated coefficient for FAR ANALOGY, $\beta = .63$, odds ratio = 1.88, indicated that FAR ANALOGY use was associated with an approximately 88% 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 statistically significant, Wald χ^2 (1) = 7.09, $p = .00$.

3.4. Discussion

Taken together, Study 2's results are not consistent with the hypothesis that the far analogies decreased fluency of concept generation. On the contrary, the positive odds ratios from the models indicated that the far analogies increased fluency of concept generation, even when compared to other concept-generating processes the designers might have been engaged in. These results suggest that Study 1's findings are not indicative of the impact of only unproductive far analogies, but they might be suggestive of far analogies spurring more functionally local conceptual search.

4. Study 3

In Study 3, we sought to provide additional tests of the potential relationship between FAR ANALOGY use and local conceptual search. One potential interpretation of the suppression of distance observed in Study 1, in tandem with the increased fluency found in Study 2, could be that the far analogies were being used to more deeply explore certain regions of the design space. Rietzschel and colleagues (Rietzschel, Nijstad, & Stroebe, 2007; Rietzschel, De Dreu, & Nijstad, 2009) have argued that novel concepts can often come from deep exploration within conceptual categories; because there are only a limited number of "conventional" concepts within categories, and initial forays into categories will tend to be superficial and be biased toward conventional ideas, extended exploration within categories can allow problem solvers to reach highly novel concepts within those categories. This conjecture is consistent with the findings of "extended effort" effects, where within an idea generation session, ideas generated later tend to be more novel than ideas generated earlier (Basadur & Thompson, 1986; Beaty & Silvia, 2012; Parnes, 1961). In the domain of design, Heylighen, Deisz, and Verstijnen (2007) showed that recombination and restructuring of elements within concepts for a design task (at the expense of lowering overall number of unique concepts) was correlated with more original concepts being produced.

It is possible that the designers were using the far analogies to generate variations on concepts that were different enough that they could continue to explore the design space more thoroughly. From an analogical retrieval perspective, too, one might expect to see such an effect of FAR ANALOGY use (i.e., generating more hops than jumps) in the context of relatively functionally coherent conceptual exploration; analogical comparison of two or more isomorphic or structurally very similar knowledge/solutions (as is the case with our data) can aid in the formation of an abstract schema through structural alignment (Gentner, Loewenstein, & Thompson, 2003; Gick & Holyoak, 1983; Loewenstein, Thompson, & Gentner, 1999), which can serve as a stronger base for retrieval of superficially dissimilar but structurally similar analogs from memory (Gentner, Loewenstein, Thompson, & Forbus, 2009; Kurtz & Loewenstein, 2007). However, this mechanism for increasing the probability of retrieving far analogies may also strongly favor retrieval of functionally very similar solutions, as structural similarity is the primary retrieval cue. Thus, observing a relatively coherent pattern of conceptual exploration JUST PRIOR to far analogies may help to explain why far analogies might be associated with incremental conceptual moves rather than jumps; far analogies may be more likely to be retrieved during an episode of exploration of variations on a common functional theme, and these far analogies are likely to be also functionally similar to the concepts being considered in that episode due to structural alignment.

4.1. Methods

To explore this potential explanation of the association between far analogies and reduced functional distance of search, we examined the concepts immediately preceding far analogy-to-concept pairs (i.e., far concept-generating or function-finding analogies), focusing on the distance of each concept from its immediate predecessor (i.e., its JUST PRIOR value, derived from Study 1). In building this sample of concepts, we screened out concepts that were not in the same subproblem space as the concept following the analogy, and concepts with predecessors in a different subproblem space. The final sample consisted of 57 concepts. The research question pursued was whether these concepts would, like the concepts preceded by far analogies, also be more likely to be functionally similar to their immediate predecessors, compared to baseline conditions. We used the 81 baseline concepts and 95 baseline concepts from Study 1 as the baseline benchmarks.

4.2. Results and discussion

Forty-one of the 57 concepts (72%) were themselves “hops” (i.e., distance of less than 3) from their immediate predecessors, although with far fewer “hops” among that set than in the set of concepts following far analogies (see Fig. 3 for a visual comparison of the distributions for functional distance from JUST PRIOR values for concepts in baseline conditions, preceded by far analogies, and preceding far analogies).

In statistical terms, the concepts that immediately preceded the FAR ANALOGY-concept pairs were less distant from their immediate predecessors compared to both 10-line window baseline concepts, Cohen's $d = -0.38$ (95% CI = −0.64 to −0.09), and 5-line window baseline concepts, Cohen's $d = -0.30$ (95% CI = −0.56 to −0.03). The former contrast was statistically significant at the conventional $\alpha = .05$ level using an independent samples t test, $t(136) = 2.17$, $p = .03$, while the latter contrast was marginally significant using the same α level with an independent samples t test, $t(150) = 1.78$, $p = .08$. These data suggest that the far analogies were often situated in a stream of relatively coherent conceptual exploration, where successive concepts (at least three in a row, two before the analogy, and one after) were variations of each other within a region of the design space.

5. General discussion

5.1. Summary and interpretation of findings

In summary, three studies were conducted to unpack in detail the effects of FAR ANALOGY use on conceptual search patterns in the naturalistic conversations of a real-world professional design team. Study 1 showed that the use of far concept-generating analogies was not associated with increased functional distance of proposed concepts from their predecessors. In fact, there was evidence that FAR ANALOGY use was temporally associated with *decreased* functional distance of search relative to immediate predecessors. Study 2 examined whether this effect was associated with an overall fixating effect, and showed that rather than decreasing the fluency of concept generation, far concept-generating analogies were associated with increased fluency, both during and after their use. This result

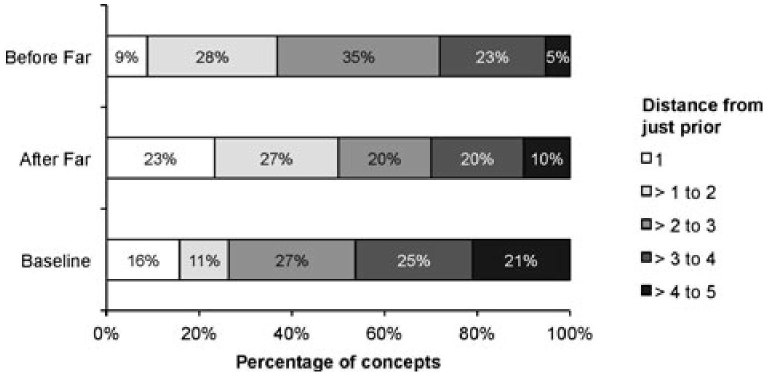

Fig. 3. Percentage of concepts at 5 distance from JUST PRIOR cutoff points, presented for baseline concepts, FAR ANALOGY concepts (defined at the 5-line window), and concepts immediately preceding far analogies.

helped to clarify the nature of FAR ANALOGY's impact on concept generation; rather than generally slowing down concept generation, the far analogies appeared to be used to keep the flow of concepts moving, with a special emphasis on generating functionally incremental steps in the conceptual space. Finally, in Study 3, we conducted an analysis of conceptual search patterns JUST PRIOR to FAR ANALOGY-concept pairs and found that concepts preceding FAR ANALOGY-concept pairs were also more likely to be functionally more similar to their predecessors (compared to baseline concepts). Altogether, the three studies suggest that, contrary to some previous accounts of creativity, far analogies may not lead to novel concepts via jumps in conceptual space; rather, far analogies may be embedded in and supportive of coherent streams of conceptual exploration, perhaps in support of a search for functionally novel concepts via deep search. To ground these quantitative observations and illustrate the effects found in the three studies, here we present two extracts from the transcripts that illustrate conceptual explorations involving far analogies.

In Table 13, 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 far analogies are employed to generate two distinct variations on this concept: 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 retains the core concept of a retractable cover, but using a slightly different mechanism, similar to a rolling garage door. Here, we see how both analogies were a source of concepts, and how the FAR ANALOGY to the garage door provided a way to further explore the space of retractable covers.

In Table 14, the designers are searching for concepts that address the subproblem 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

Table 13
Example of progression in conceptual exploration involving FAR 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 62		
1525	Rodney	garage door well it could be a roller
1526	Todd	a roller door

Table 14
Another example of progression in conceptual exploration involving FAR ANALOGY

Concept 24		
692	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 sort of some feedback
730		in terms of colour LEDs on the pen saying that he's done a good or she's done a good job or-laser levellers
Analogy: DIY		
777	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 levellers and things like that
Concept 28[a]		
779	Alan	if you had like a little laser that made sure that 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

Note. [a]Concept numbers not contiguous because concepts relating to other subproblems were discussed in between Concept 25 and the analogy.

achieve that angle of contact without some help. 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). Concept 25 takes the idea of feedback in a slightly different direction and proposes giving visual (as opposed to simply tactile) feedback to the user to guide interactions. This delineates a region of the design space with the general approach of providing perceptible feedback and sets the stage for a FAR ANALOGY to laser levelers, used among DIY enthusiasts to make sure they are following appropriate angles for various construction and re-pair tasks (e.g., laying tiles, constructing shelves, etc.). Again, as in Table 13, this analogy was a direct source of Concept 28, which spurred further exploration within that region of the design space 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 far analogies were a significant source of concepts that tended to be embedded in and supportive of continued explorations in particular functional regions of the design space, rather than large functional jumps.

5.2. *Caveats*

Some caveats should be mentioned before discussing the broader implications of this work. First, the present empirical 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 lend 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. Nevertheless, our data have several mitigating factors that lend strength to the internal validity of the findings, namely the high reliability of the measures (e.g., $k > .8$, ICC $> .9$ for analogy distance and concept functional distance, respectively), the descriptive analysis of the frequency distributions of functional distance of concepts addressed by far analogies versus not, the analysis of the analogy-concept extracts from the transcript in the discussion, and the examination of *temporal* order.

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 concept generation, are highly resource intensive, making comparisons across multiple expert datasets difficult. From one perspective, the sample size of the three studies was essentially $N = 1$, given that only one team was studied. Nevertheless, the high external validity of the data does provide some initial confidence that the observed interplay between far analogies and conceptual search patterns is as likely to generalize to other real-world contexts as studies conducted in the laboratory. Further, the team worked on many different subproblems, and thus the observed pattern is unlikely to be driven by characteristics of a single problem; many laboratory studies employ many participants, but all participants often solve a particular problem.

The restriction to one team also precludes our ability to relate the observed patterns directly to final creative outcomes; thus, only descriptive (*not* prescriptive) inferences are supported by our data. Our data are silent on whether the patterns of relationships between far analogies and conceptual search patterns are low-performance or high-performance creative concept generation strategies. Yet the designers were experienced, professional designers at a firm known for innovation, suggesting that the patterns observed may represent an expert concept generation strategy involving far analogies.

Finally, some might be concerned about our reliance on verbal reports as data. Such methods can suffer from loss of signal; however, the critical question is whether our loss of signal is *systematic* in a way that undermines our analyses and inferences. For instance, our choice to measure verbally expressed analogy precludes measurement of “implicit” analogy (i.e., mappings that occur below/without conscious awareness); however, given that most theories of analogy assume the central mapping process occurs in working memory, we do not believe that these implicit mappings are actually analogy at work (see, e.g., Schunn & Dunbar, 1996). With respect to explicit but not verbalized analogies, we believe the interactive nature of the design meetings helps to mitigate concerns about missing such analogies. Transcripts of collaborative discussions can be thought of as approximating the level of explication of thought in individual verbal protocols, as the collaborators have an incentive to provide common ground for collaborative problem solving, particularly given the multidisciplinary context. There could also be a systematic loss of signal biasing against truly far analogies due to social inhibition; however, we believe this is not present in our data, as the designers were given standard brainstorming instructions to encourage wild ideas, had been working together for many years, and many outlandish things were said in the meeting (e.g., evil emperor from Star Wars with lightning bolts shooting out of nose, joking that they should teach left-handed children to be right handed by hitting them with a cane). For these reasons, we accept that there is some loss of signal in our analogy measure, but we do not believe that there is significant or systematic loss of signal that precludes our ability to draw useful inferences from the data.

5.3. Future directions

We now note some key future directions of this work. First, there is the issue of generalizability across design situations. It is possible that FAR ANALOGY-generated jumps may only occur in certain design situations. Perkins (1994, 1997) has described a potential "isolation problem" in creative problem spaces, where innovative concepts are bounded in the space by wildernesses of no promise. In these situations, incremental search may lead to an impasse, as there is no incremental path into the location of the innovative concept 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 consistent with 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.

The data we have do not allow us to speak directly to this issue, as we did not measure the occurrence of impasses; we did have an indirect measure of impasses (i.e., expressed uncertainty in their speech; for more information on the measure, see Ball & Christensen, 2009) but found no measurable difference in uncertainty levels between problems addressed by far analogies versus not. It is possible that the lack of increased uncertainty for problems addressed by analogy indicates a lack of impasses and therefore reduced likelihood of or need for large jumps; however, jumps did occur for problems not addressed by analogy, which had comparable levels of uncertainty (or lack thereof). Thus, our data are inconclusive regarding any potential variations in the relationship between far analogies and conceptual jumps as a function of impasses. Follow-up work may explore this issue further by creating impasse-likely and impasse-unlikely design situations and comparing the impact of far analogies on conceptual search patterns across those settings.

Further, there is the issue of self-generated nature of the far analogies in this data; 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 concept generation 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 of the local/incremental character of conceptual search supported by FAR ANALOGY might be that many of the far analogies were insufficiently "far" from previously considered concepts.

That is, notwithstanding the documented capacity of people to retrieve far analogies from long-term memory in naturalistic settings (Blanchette & Dunbar, 2000; Dunbar, 2001), it is possible that, given the computational constraints of analogy (e.g., preferring systematic matches, one-to-one mappings; Gentner, 1983), the strong influence of surface similarity on retrieval (Forbus, Gentner, & Law, 1994; Gentner & Landers, 1985; Gentner, Rattermann, & Forbus, 1993; Keane, 1987; Rattermann & Gentner, 1987; Reeves & Weisberg, 1994; Ross, 1987), and the associative character of memory (Collins & Loftus, 1975; Raaijmakers & Shiffrin, 1981), designers might not be able to retrieve from memory other concepts that solve similar subproblems in very different ways, especially if these concepts are embedded within designs or products with very different overall functionality. Further, as noted earlier, most of the far concept-generating analogies appeared to have been retrieved within an episode of relatively coherent functional exploration, providing further constraints on the range of functional distance the designers could explore using analogical retrieval.

Different effects of analogy on conceptual search patterns might be observed with externally provided analogous sources that are highly distant functionally. Perhaps very far (even bordering on "random") analogical stimuli from external sources are needed to truly support large conceptual jumps into novel search space territory. It is worth mentioning, however, that the current empirical support for the benefits of "random" analogies is mixed at best (for a recent review, see Christensen & Schunn, 2009a). There are also potentially important interactions between problem space structure and analogical source. It may be that far analogies retrieved from memory generally support increased fluency of search but enable jumps out of local maxima only in impasse situations, and perhaps only if they are "far enough" (e.g., from "random" external sources). Future work should explore these novel hypotheses.

5.4. Broader implications

We conclude by noting some broader implications of the work for understanding innovation in general from a cognitive standpoint. One potential insight might be an elevation of the importance of incremental/iterative development of concepts as a pathway to novel concepts. Insofar as far analogies in the concept generation process are associated with more innovative outcomes, we might infer from the present data that incremental accumulation of many small insights is at least as likely to lead to innovative outcomes as direct generation of very novel concepts. The history of innovation contains accounts of such "incremental" accumulations that culminated in innovative breakthroughs; one striking example is the invention of the steam engine by James Watt, which was powered in large part by a crucial addition of a steam condenser (for increased efficiency of the heating/cooling mechanism of the metal cylinder in the steam engine) to Newcomen's "atmospheric engine"—this relatively small addition proved to be such a difference maker that

James Watt is often credited for the invention of the steam engine. Detailed *in vivo* and cognitive-historical accounts of innovation have also highlighted this very incremental pathway to highly innovative outcomes (Carlson & Gorman, 1990; Gorman, 1997; Weisberg, 2009).

Another potential implication might be a rethinking of the impact of analogical distance. If the cognitive mechanisms by which far analogies inspire innovation are shown to be very similar (or identical to) the inspirational mechanisms of near analogies (e.g., increased fluency), this might provide some motivation to question the fundamental distinction between far and near analogies in terms of their potential for supporting innovation. It may be that it is not analogical distance from one's problem per se that matters, as Perkins (1983) and Weisberg (2009) argue, but other considerations, such as the similarity of the analogical source to one's currently considered concepts, or the relationship of the analogy to other considered analogies (e.g., conceptual diversity of sources considered; Mumford, Baughman, & Sager, 2003; Taylor & Greve, 2006). Certainly, much more theoretical and empirical work is needed to evaluate whether this theoretical questioning is warranted.

Overall, the present work highlights the important and complementary role of detailed *in vivo* studies of cognition for a complete cognitive science of innovation; just as protocol analyses of online problem solving yielded invaluable insights that constrained theories of problem solving and aided in suggesting hypotheses for and guiding interpretations of experimental studies, so *in vivo* studies of the innovation process can continue to complement experimental data from input–output studies and inform more complete theories of the cognitive processes that lead to innovation.

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